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An industry 4.0 approach to electric vehicles

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ABSTRACT

Energy and environmental impacts are at the top of the list of major global challenges to be addressed within the next few years. With transportation being one of the most pollutant sectors, focus has been directed towards Electric Vehicles, due to their significantly less dependency on fossil fuels. Nevertheless, electric mobility is currently characterized by a limited driving range, leading manufacturers to investigating new methods that could increase range and charging efficiency. Current research is mainly focused on increasing battery performance and reducing charging time. This study concentrates on presenting a novel approach, based on replacing battery stations, where the vehicle's batteries are replaced with a fully charged one (available at the station), while new modular batteries could be made on the spot. The existing gas station networks could be used for the replacement of electric car batteries. This will be addressing the issue of time-consuming charging of batteries. Through the assimilation of Industry 4.0 Key Enabling Technologies, the respective challenges can be addressed. This is illustrated through a holistic framework, whereby the requirements for the context-aware design of the car itself are also given and a specific solution, based on the mechanical mounting of batteries is discussed..

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1. Introduction

Car manufacturers enter the space of the electric vehicle (EV) (Gnann et al. 2018; Nanaki 2021). This is highly correlated to the fact that the consumers find the green aspect very appealing (Rezvani, Jansson, and Bodin 2015). Reduction in the consumption of the emissions and the resources (Athanasopoulou, Bikas, and Stavropoulos 2018) are also in support of this trend. Moreover, the green agenda in Europe seems to have had a great impact on manufacturing in general ('White Paper 2011 | Mobility and Transport' 2021). Statistical figures show the correlation between market uptake and GDP, in the European Union (EU), with Germany, the United Kingdom and France having the highest EV market share in the EU for 2018, highlighting the importance of the EV market ('Interactive Map – Correlation between Uptake of Electric Cars and GDP in the EU – ACEA – European Automobile Manufacturers' Association' 2021; Hanžič, Marksel, and Božičnik 2019). Electric vehicles, in particular, seem to be having a very specific related issue, that of the battery. Some intelligence (Arora, Shen, and Kapoor 2016; Albright and Kappel 2003) has been embodied in the design of the car and the battery, but the issue of its charging still remains, despite the fact that the stakeholders' number has now been increased drastically, by offering many differentiating choices

Moreover, given the technology maturation in all related aspects, the solution of charging stations could be considered ('The Green Look for EV Charging Stations | News | CORDIS | European Commission' 2021). There are issues, whose solution such as the variability in the design, is still pending. Within the last years, several efforts have been made in terms of modular battery solutions and the optimization of battery charging stations that have been elaborated in the following section (Zheng et al. 2014; Min, Yang, and Wang 2020; Hao et al. 2018; Paralikas et al. 2011).

The research question that has been asked in this study is; How Industry 4.0 (I4.0) can help in exceeding the challenges for the replacing batteries business model. The key suggestion and novelty is the evaluation of a framework for the replacement of batteries, at intermediate stations (including existing gas station),

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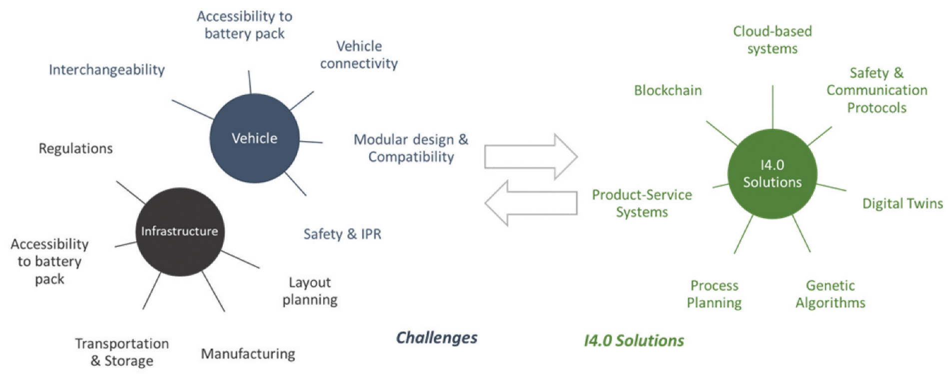

Figure 1. Research methodology.

enhanced though, with the newly introduced I4.0 Key Enabling Technologies (KETs). The research methodology that has been followed in this study focuses on the link between I4.0 and EV challenges (Figure 1). Challenges considering the required infrastructure of the replacement battery stations, as well as the infrastructure of the EV, have been examined and distinguished into safety, operational and connectivity issues. Envisaged I4.0 solutions have been searched which can sufficiently address such issues and ensure the efficient distribution and safe operation of the battery replacement stations network.

The rest of this paper is structured with a brief literature review in section 2, while section 3, contains the approach. The challenges are presented in section 4 and finally, the acquired outcomes are included in section 5.

2. Literature review of battery modularity for electric vehicles

Modularity in the automotive industry targets at repairs and maintenance by making substantial components of the vehicle interchangeably. Initial attempts are being made in the EV design in order for the modular exchange of batteries to be enabled. Fiat introduced the Centoventi concept car (2019) as a customizable and upgradeable EV, by providing the capability of designing a modular battery in the range of a maximum of 500 kilometers. The Volkswagen (VW) Group has developed the Modular Electric Propulsion (MEB) Platform; a modular electric cars platform, planned to be integrated into the production of VW Group electric cars from 2019 to 2025. XING Mobility released the Immersion-Cooled Modular Battery Pack System in 2017, a modular battery back system, consisting of Lithium-ion battery cells, directly fused into 3 M Novec Engineered Fluid to enable custom configurations and improve battery life.

Pertinent to the manufacturing and dispatching of the batteries and the cars, there are concepts that recent research literature is focusing on (dematerialization, energy efficiency, design for assembly, zero defect, predictive maintenance, analytics) (Annarelli, Battistella, and Nonino 2016; Petrides et al. 2018). Consequently, it seems that the distributed charging may find more than one really enhancing factors and multipliers in the manufacturing era, due to I4.0. Modular design can be the basis for this (Burda et al. 2012); however, the I4.0 KETs utilization (Muhuri, Shukla, and Abraham 2019) is expected to determine, to a great extent, the success of this concept.

There is a plethora of studies that are indicative of the implicated technologies, being at the correct readiness level. The monitoring of the car's status is highly relevant to such applications (Silva et al. 2018). In particular, the Battery Management System (BMS) architecture should render processing data feasible and facilitate the monitoring of the modular battery pack (Arora 2018). Cyber-physical systems (CPS) & Internet of Things (IoT) concepts integration for monitoring, have been discussed formerly for the estimation of the time in order for the nearest available charging station to be reached (Savari et al. 2020; Alexopoulos et al. 2018). Battery monitoring via IoT can be also examined (Friansa et al. 2017), as well as the prediction and optimization of energy management (Barsukov, Qian, and House Bostonlondon 2013; Brand et al. 2016), battery diagnostics, data collection etc. (B. Wu et al. 2020), while the digital twin framework seems to be valuable for battery life monitoring.

The next set of technologies is related to the design of the car itself and the space of the batteries (Breban 2016; Gong et al. 2020) apart from the design of the modules as well as for the connectivity (in series or in parallel) of the cells/modules (Viswanathan, Narayanan Palaniswamy, and Balaji Leelavinodhan 2019). The cooling system should be also considered at this point. Several attempts have been made for the examination of novel liquid/air cooling strategies (Yang et al. 2020; Akinlabi and Solyali 2020; Zhou et al. 2019; Wang et al. 2020). At the same time, the interconnection among the modules is highly relevant (Brand et al. 2016).

The packaging of the modules has also been raised in literature; battery joining with the use of ultrasonic welding, wire bonding, force fitting/ mechanical assembly and resistance spot welding (Zwicker et al. 2020). Thermal runaways, vibration isolation, crash worthiness and material selection are all relevant (Arora, Shen, and Kapoor 2016). In addition to the mechanical absorbers, the connection to the charger and to the BMS module and their design will highly affect the final efficiency (Cui et al. 2020).

Battery assembly and disassembly is an additional issue that has been brought up having considered modularity (Wegener et al. 2015; Bikas et al. 2016). Efforts are being made in collaborative robotics and multi-objective decision making to support the assembly and disassembly process of EV batteries (Sha et al. 2011; D'Souza, Patsavellas, and Salonitis 2020; Kousi et al. 2019; Michalos et al. 2018). Assembly sequence generation methods, based on serial configuration or parallel operations, enable continuous changes in flexibility and reconfigurability, related to various design configurations (Chinnathai et al. 2017). Cloud based assembly and disassembly systems, based on cloud robotics enable adaptability to complex infrastructures and provide the capability of handling and processing the large number of data required (Singh and Janardhan Reddy 2019).

Additional effort has been made in terms of battery recharging scheduling, through the investigation of various strategies and concepts, for the reduction of the waiting time for charging. Decision-Making algorithms have been considered for facilitating the charge scheduling, within a charging station and supporting the driver to select the most appropriate station, based on their needs and preferences (Milas, Mourtzis, and Tatakis 2020). Time of Use pricing and Maximum Demand Limit have been further examined for recharge scheduling in shopping malls, targeting at scheduling charging at low price periods and reducing peak loading of the grid (Athulya, Visakh, and Selvan 2020). The scheduling aspect, has been further within literature, in terms of transmission-planning, though the development of coordinated Battery-based Energy Storage Transportation for power systems, for managing transmission congestions, aiming at the cost reduction of both stationary and mobile storage units (Pulazza et al. 2021).

3. Approach to the concept of 'replacing battery' stations

The basic approach is to use a network of 'replacing battery' stations, including the existing gas stations, for a 'quick' battery replacement (Figure 2) procedure. The replacement scenario foresees that the driver of an EV should check the status of his vehicle's batteries and if the battery status is such that it should be changed/charged, he will check if there are battery replacement stations around and will proceed to the closest battery replacement station. I4.0 KETs and IoT, which are further described in Section 5, will be used to ensure the secure communication between the

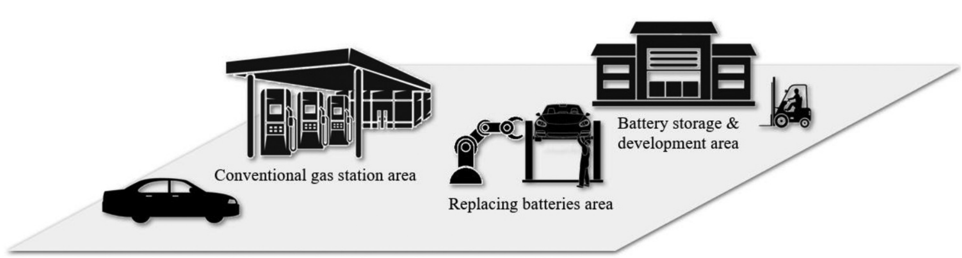

Figure 2. A replacing battery station schematically.

BMS of the vehicle and the battery replacement stations network, as well as the communication among the different departments of the battery replacement station (Amin et al. 2020; Lee et al. 2020; Vagropoulos, Kyriazidis, and Bakirtzis 2016). Initially, the dynamic pricing schemes, in the distribution charging network, could be monitored during the decision-making process of selecting the battery replacement station, er based on the driver's preferences. In the battery replacement station, a procedure will be followed, where the battery, which will be removed from this car will be placed in a designated area, where it will be recharged for as long as it is required. A new fully charged battery from the station's depot will be installed into the driver's car. The payment for the battery replacement will be made according to the status of the batteries left by the driver at the gas station, versus the state of the batteries that will be included in his car. This is somewhat the same as when a driver today in a gas station fills up his tank and pays the amount corresponding to it.

The battery is installed at the battery replacement station and it is recharged in the proper area, based on the rules and procedures adequate for the charging of this particular battery. One can envision that the duration of the battery's full replacement process might take the same time as that required at a gas station in today's environment.

There are a number of obvious advantages of such an approach, namely the quick refill of batteries, the use of the existing network of gas stations and the quick charging/payment for the battery replacement, while the batteries will be recharged by professionals safely in proper places (Figure 3). The concept allows the quick 'refill' of batteries and gives flexibility to the drivers.

4. Challenges of 'battery replacement' stations

In order for this approach to be realistically considered, there is a number of challenges that need to be addressed, possibly with the help of I4.0 concepts and KETs.

They can be categorized into two major groups;

- the one that has to do with the *infrastructure* issues and
- the other with the *vehicle* issues.

Regarding the infrastructure issues, one should consider the proper structure, design and functioning of the replacing batteries station, namely the building, the electric power processes, the replacement processes, the tools to be used for the replacement etc. These challenges are interwoven with the challenges of the vehicle, whereby one can think of new batteries being designed lighter so as to be easily replaced. One also needs to consider the vehicle design in terms of modularity and easy-to-access batteries, dictated by the concept of quick battery replacement. In the following sections, these challenges will be also discussed in view of I4.0 KETs aspects.

4.1. Infrastructure challenges of 'battery replacement' stations

The selection of the replacement station is based on the availability of the station's assembled battery packs, which are compatible to the driver's car, as well as on their charging status, indicating their readiness to be mounted onto the car. In case that a charged battery pack is not available in the station, but it can be made on the spot, the time required for the building and charging of a new battery pack will be provided to the driver in order for him/her to decide whether he/she should reach the station or not.

The development of a distributed network of battery replacement stations, including the existing gas stations, foresees the integration of the additional infrastructure, which can enable the replacement, building and charging of the modular battery packs for as long as required. The battery replacement stations will be a standalone infrastructure in the distributed network or will be incorporated into the conventional gas stations, in a certain area, in compliance with functional, safety and environmental regulations.

Arriving at the battery replacement station, the vehicle will be driven to the 'replacing batteries' area. Collaborative robots will have access and remove the discharged battery pack from the vehicle. The discharged battery pack will be transferred to the 'battery charging' area, where the condition and charging status of the battery will be monitored, and the battery will be recharged. Once it has been fully charged, the battery based on its compatibility will be transferred to the 'batteries storage' area, ready to be mounted to another vehicle.

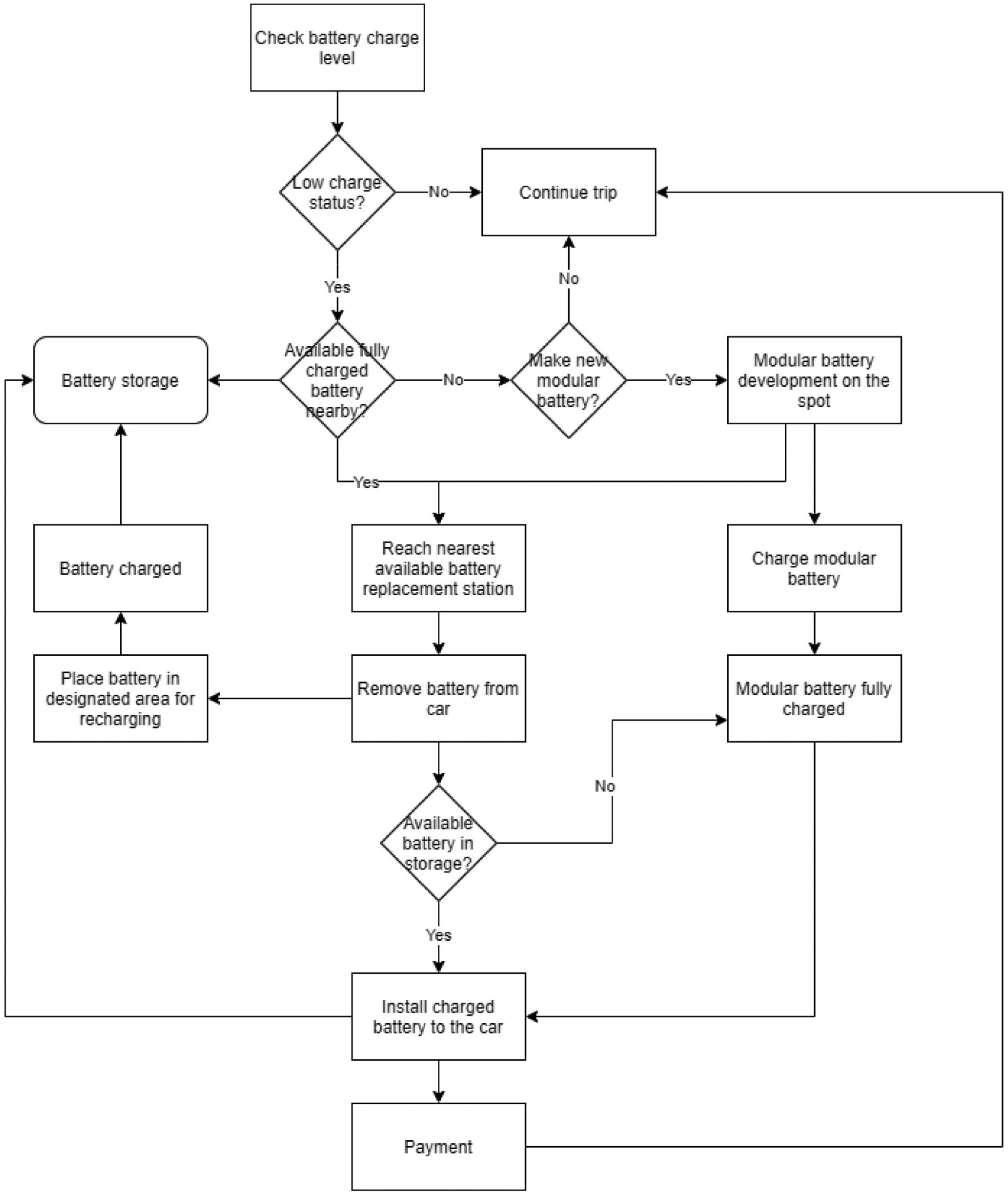

Figure 3. Battery replacement procedure flowchart.

Following the discharged battery removal from the vehicle to the 'charging batteries' area, a charged battery is to be installed into the vehicle. The selection among available charged batteries in the 'batteries storage' area will be primarily performed. In case that a compatible battery to the vehicle's model is available, it will be transferred to the 'replacing batteries' area and mounted to the vehicle.

Considering that no available batteries are stored, the driver has selected a priori the particular battery replacement station in order for a new modular battery to be developed that fits to his vehicle. The modular battery is being designed and developed in the 'battery development' area. Having the new modular battery developed and assembled, it is transferred to the 'replacing batteries' area to be installed to the vehicle. The required time for building and assembling the battery should follow the estimated time delivered to the driver, during the battery replacement station selection.

Layout planning for the installation of the required infrastructure, including the different workstations and battery integration areas, should be in compliance with functional, safety and environmental regulations. Potential issues on the electricity network, due to the high-power requirement, should be monitored and addressed to support the continuous and efficient operation of the entire battery replacement stations network.

Monitoring, communications and data processing technologies under the concept of I4.0 could have high potential on both the accurate vehicle status monitoring and on replacing the battery station selection as well as on the efficient integration and communication among the different infrastructures. In particular, the following I4.0 concepts have been considered, technology-wise, as the potential solutions to the proposed framework towards the transition to replacing battery stations. Figure 4 illustrates the areas where the I4.0 solutions apply, based on the layout of the battery replacement stations, having considered the envisaged workflow.

- Sensors networks, CPS & IoT for monitoring the real-time status of both the battery packs and the replacing of the battery stations network
- Additive Manufacturing for jigs and plugs for facilitating the manufacturing process of mechanical assembly and the fitting of the battery packs
- Augmented Reality for facilitating the operators during the assembly and the battery replacement process, through the use of holographic guidance
- Cyber Security for Big Data protection and accurate communication among the several tasks and departments, to enable the fast and efficient battery replacement
- Collaborative robots, mobile robots, vehicle hoists and additional equipment should be provided for the integration and transfer of the modular batteries, across the different departments of the station.
- System Integration for efficient layout planning and optimization for the physical setup of the equipment
- Cloud Computing for distributed Decision Making in process planning and scheduling

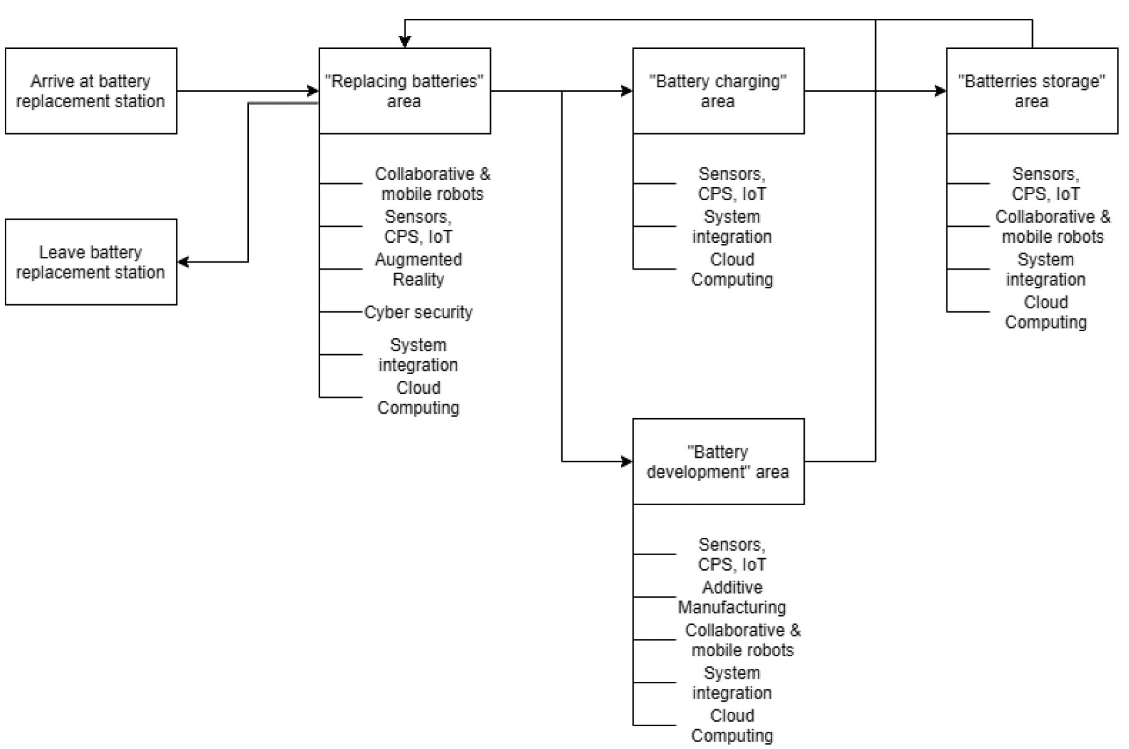

Figure 4. Overall I4.0 integration.

4.2. Vehicle challenges for 'replacing battery' stations

Furthermore, the main challenges for the implementation of this approach are related to physical and mechanical aspects. Such aspects involve the technical characteristics, in terms of battery efficiency and performance to meet the manufacturer's criteria, namely, connectivity, safety and monitoring. The following parameters considered in this study have been categorized in terms of the modular structure and connectivity of the battery assembly, the electrical components and safety.

The first category is related to the geometry of the batteries and the battery packaging space. The entire battery system is being monitored through BMS. The accurate and efficient operation of the BMS is crucial for the protection of the battery and the maintenance of a safe operating area. The state of the battery is monitored by the BMS, through the acquisition and the processing of data, related to voltage, temperature, coolant flow and current, that can be interpreted into necessary information, regarding the state of charge, battery condition, voltage protection and cell health (Barsukov, Qian, and House Bostonlondon 2013). The connectivity between the modules and the battery cells, in the entire battery pack, should be also considered. This is related to the configuration and connectivity (in series or/and in parallel) of the cells to larger modules, and the integration of the modules into the battery pack that includes electronic management controlled by the BMS. In order to analyze and correctly interpret the acquired data, based on the manufacturer's specifications, accurate data processing should be ensured. In addition to challenges related to the battery assembly geometry, the positioning of the battery pack from the workstation to the battery packaging space, should be considered. During the processes occurring in the battery swapping station, access should be guaranteed to the vehicle's battery pack in order to enable the integration of the modular pack, along with the mechanical transfer and mounting.

Relevant to the battery geometry challenges that should be taken into account, are the electrical characteristics. This comprises the consideration of the electrical plug position and connectivity to the battery pack, as well as the electrical charging constants. These parameters could be considered as the peripherals systems of the manufacturer's battery pack to be connected to the modular battery pack, without hindering the charging performance.

Furthermore, issues related to safety charging and the safety having to do with the mechanical behavior, should be considered. The developed modular pack should be continuously monitored by the BMS in order for the efficient and safe operation to be guaranteed, at any state of charge, and the user or/and stop navigation to be warned in case of an unexpected condition.

Finally, IPR barriers seem to have a major contribution to hindering the implementation of this method (Schmitt et al. 2016; Hartwell and Marco 2016).

5. Envisaged I4.0 solutions

I4.0 KETs could deliver promising solutions on the generated challenges and issues, related to the vehicle design and the modularity of batteries (Figure 5).

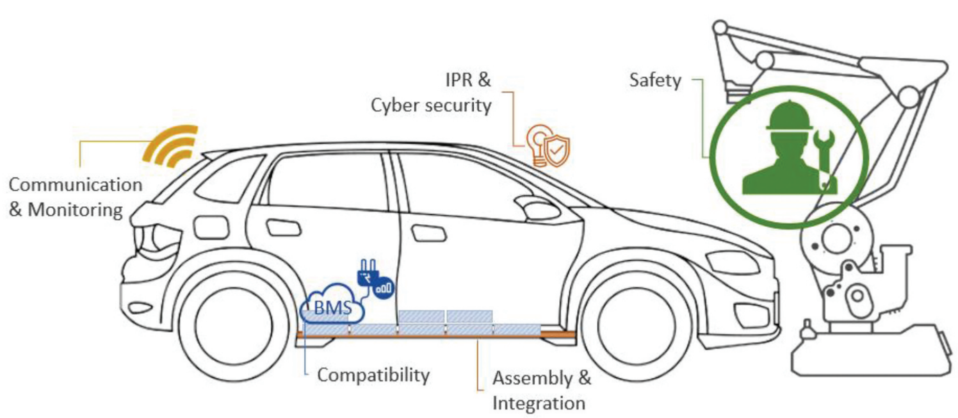

Figure 5. Diagram depicting challenges.

This involves the use of I4.0 concepts in various tasks during the development and efficient integration of the modular battery pack, as well as during the accurate monitoring of the battery condition and state of charge.

- Cloud-based BMS and the use of Digital Twins could deliver real-time and accurate processing of data obtained from the modular battery pack in order for the vehicle designer's specifications (Weihan et al. 2020) to be met
- Context aware design of modular configurations, through the Genetic Algorithms for the modular design and connectivity (in series or in parallel) of the battery cells and modules (Breban 2016)
- Process Planning with main criteria cost, time, safety (i.e. heat during welding) and circularity (Gallagher and Nelson 2014)
- Product-Service System, as a hybrid technical-business model, to solve intellectual property rights (IPR) data (Meier, Roy, and Seliger 2010)
- Blockchain towards certification and IPR
- Safety Network protocols (CIP Safety, PROFIsafe, openSAFETY, FSoE etc.) and communication protocols used for the automation of processes (AS-I, BSAP, ControlNet, DeviceNet, CC-Link Industrial Networks, DNP3, UAVCAN etc.) to ensure safe operation of machinery in the replacing battery stations

5.1. *Designing the proper geometry for the car*

The battery configuration follows the vehicle model's specifications in terms of battery packaging space and its capacity. Based on the battery packaging space allowed for each vehicle model, an initial configuration of the battery geometry could be estimated on the basis of a LEGO-like structure. The battery pack will be formed by stacking each block (module) within the allowed space. The battery pack design could be divided into two phases; the definition of the number and size of modules in line with the vehicle specifications, in terms of battery capacity and voltage, and the design of each module via the Deep Learning and Genetic Algorithms for the estimation of the cell number, module and pack structure, connectivity and cooling.

5.2. *Building the modular blocks*

Supportive structures, based on the design specifications of the module, in terms of the number and connectivity of the cells, should be built. The connectivity and integration of cells and modules could be performed through ultrasonic welding, wire bonding, force fitting/ mechanical assembly and resistance spot welding (Zwicker et al. 2020).

For the assembly of modules in the battery pack, a LEGO-like structure could be considered. Thermal runaway, vibration isolation, crash worthiness and material selection should be taken into account (Arora, Shen, and Kapoor 2016; Chung and Soo Kim 2019). Additionally, the peripherals integration involves the design of the mechanical absorbers, connection to the charger and to the BMS module. The vehicle's BMS is designed on the basis of a certain battery model/ technology. Considering that the modular battery pack replaces a different battery type (i.e. battery consisting of a different type of cells or a different cooling mechanism), modifications on the BMS should be made in order to process data and to monitor the modular battery pack (Arora 2018). A module could be designed for the connection of the vehicle's BMS and the integrated battery pack by calibrating the data, acquired from the battery pack to be transformed into information that can be processed by the BMS. I4.0 KETs, in particular the Big Data, IoT and Cloud Computing could deliver the real-time processing, monitoring and calibration of information, acquired from the vehicle's BMS for the efficient interpretation of data, obtained from the modular battery pack (Papacharalampopoulos et al. 2020).

5.3. *Final manufacturing and assembly*

Accessibility is a key-factor for the success of the above scenario. Certain requirements and restrictions should be considered for the integration of the modular battery pack into the vehicle. This includes the acquisition of access to the battery packaging space, a unified and share design and protocols, shared tools and infrastructure and licence offer to the stations. To this effect, battery modularity should be considered during the design phase of the entire vehicle, in order for easy access and unmounting of the battery pack to be provided without requiring the disconnection of components from the interior and the chassis. From the engineering point of view, facilitating the mounting of a battery is considered being an extra design goal for the car, apart from the distribution of weight in a plane and mass center position. One could consider the use of I4.0 KETs for the facilitation of the entire battery assembly process planning and integration to different EV models. Additionally, the Human Robot Collaboration (HRC) shows potential on addressing the requirement for modular product development with the use of smaller lot sizes. Collaborative robots deliver significant benefits, with respect to the implementation of production cells, which can easily change their operation for different product families (Michalos et al. 2018; Mingwei, Wang, and Pan 2020). These are great capabilities for the implementation of HRC into the replacing battery stations, by providing increased flexibility and high reconfiguration in the production of modular batteries, while enabling complex operations in smaller lot size.

- Collaborative robots, communicating with each other to perform specific tasks, could be utilized for transferring and integrating the entire battery assembly to the battery packaging space of the vehicle (Papakostas et al. 2014).
- The overall unmount and mount process should rely on flexibility and adaptability, through a knowledge-based automated assembly process planning concept, in order to provide feasibility to different vehicular infrastructures (Bikas et al. 2016).
- The exploitation of virtualization techniques, along with the digital twin platforms would be of high importance for a context-aware design and efficient weight distribution (Figure 6). This would be enhanced to a further extent by incorporating modified assembly algorithms.
- The mechanical connection between the cage and the box, as illustrated in Figure 7, is performed with linear and crashworthiness (L&CW) elements. These are directional elements (operating per axis) allowing the smooth motion of the box, while preventing the box from being distorted in the unlikely case of a crash. The structure of these elements is shown below in Figure 7; their linear part in its simplest form, consists of a damper and a spring, while a porous material, capable of absorbing energy at large forces, is also present. These elements ought to be maintainable, so that they could be mounted onto the cage with some sort of rotational link. The IoT-based sensors and actuators could deliver advanced battery pack protection and real-time monitoring for adaptive motion cancellation.

6. Discussion

Globally, the transformation of the manufacturing sector towards digitalization, is setting the scene for a radical industrial change. Major expectations, in terms of operational effectiveness to the increase of value, result in the increase of interest towards the implementation of I4.0 new technologies and concepts. Nevertheless, the integration of I4.0 KETs into the automotive industry, and consequently into the battery replacement stations, is not a straightforward decision (Stavropoulos et al. 2021). Comprehensive strategies and methodologies are followed by many organizations to ensure their strategic

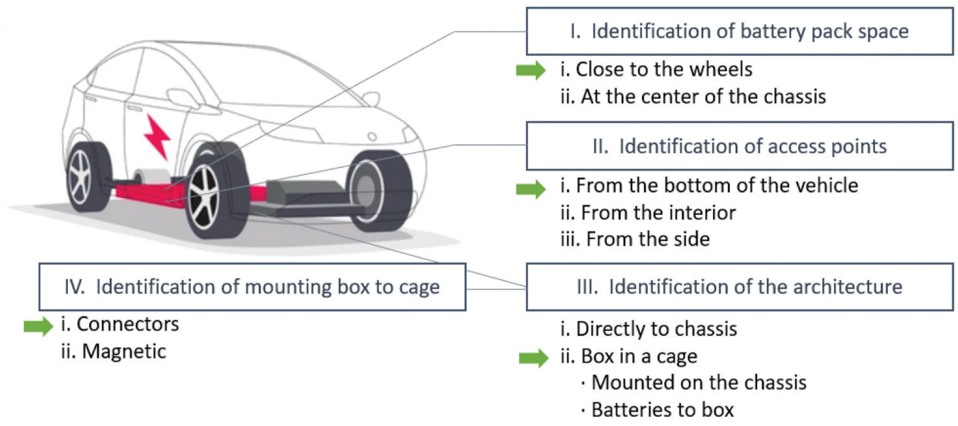

Figure 6. Interpretation of the context aware design using a box-in-a-cage approach.

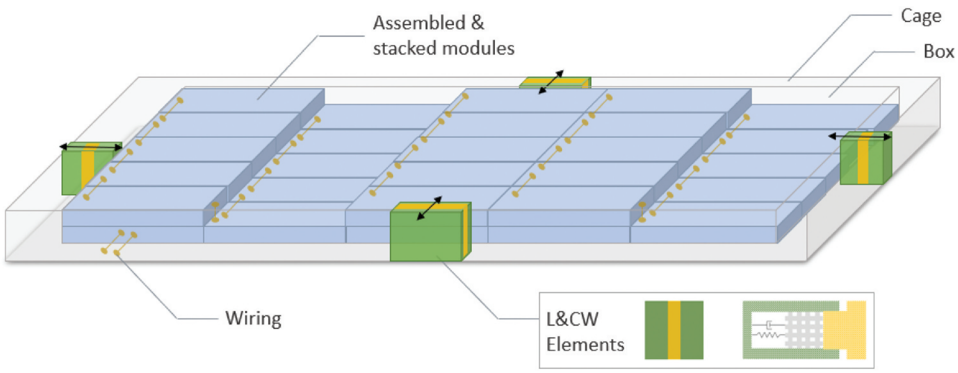

Figure 7. Cage-Box mechanical & electrical connectivity including L&CW elements.

orientation towards this transformation. In order for their digital transformation roadmap to be defined, digital maturity models are followed by the enterprises to link the existing organizational and operational knowledge to novel concepts (Colli et al. 2018). Within this context, the potentiality of implementation of I4.0 KETs, based on the maturity level of the manufacturing sector, should be considered for the efficient development and distribution of the stations' battery replacement network.

Significant effort has been made for the development of various maturity models, based on different strategies for evaluating the company's current status and supporting its transition, during the implementation of I4.0 concepts (Yagiz Akdil et al. 2018; Schumacher, Erol, and Sihn 2016). To evaluate the readiness level of the manufacturing sector, under the prism of the battery replacement stations concepts, the existing literature has been considered for the evaluation of the maturity and road mapping in I4.0. Previous studies on holistic and specific approaches have been investigated in order to extract the maturity dimensions and assessment items, related to the implementation of the required I4.0 KETs by the manufacturing sector for the development of the stations' battery replacement network. (Schumacher, Nemeth, and Sihn 2019) have suggested a maturity model, based on Hevner's design science approach for the development of artifacts to capture real-world problems (Hevner et al. 2004). (Rübel et al. 2018) used a multimethodological approach, based on conceptual modelling and qualitative and quantitative strategies for empirical validation. (Colli et al. 2018) have developed an approach on the Problem Based Learning model for providing contextualization during the maturity assessment process. Based on the previous studies, eight dimensions have been extracted to depict the maturity level (1–5) of the manufacturing sector, after having considered the results of five different manufacturing companies (Figure 8).

Each of the aforementioned dimensions could be distinguished into a number of subdimensions. The particular study focuses on the technological aspect, indicating the need for further evaluation of the technology readiness level in the manufacturing sector. (Çınar, Zeeshan, and Korhan 2021) have developed a framework for the assessment of the maturity model dimensions and subdimensions, which was further evaluated with the use of a case study, based on an automotive manufacturing enterprise. Five levels, from 0 to 4, have been used for the assessment Figure 9, depicts the maturity level of the Technology subdimension, considering the I4.0 KETs required for the implementation of the battery replacement stations.

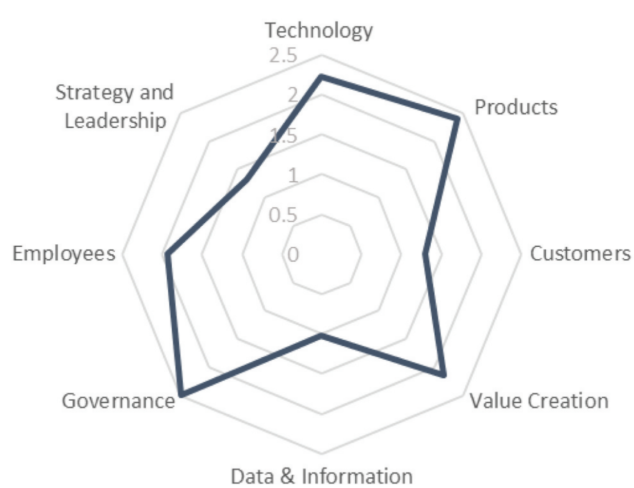

Figure 8. I4.0 maturity in 8 dimensions, based on (Schumacher, Nemeth, and Sihn 2019; Hevner et al. 2004; Colli et al. 2018).

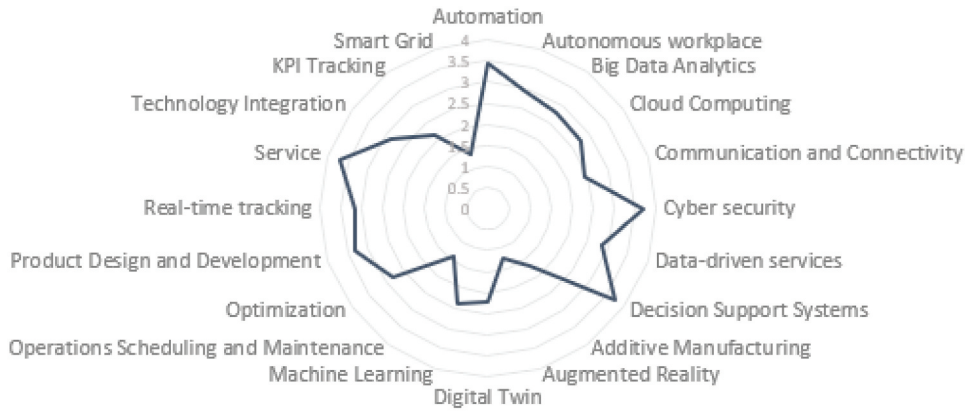

Figure 9. Maturity level of 'technology' subdimension, based on (Çınar, Zeeshan, and Korhan 2021).

Considering the above, important outcomes could be extracted for the maturity level and potentiality for the implementation of I4.0 concepts. With respect to the overall enterprise readiness, the 'Data & Information' dimension is still at a low level, indicating potential difficulties, regarding the efficient information exchange, between the battery replacement stations and the vehicle, which could result in significant issues, during the operation of the stations. Additionally, the 'Customers' dimension level, reflects the even low familiarity with I4.0 KETs, which could result in difficulties during the selection of the battery replacement station by the driver.

Nevertheless, the comparingly higher maturity level in the 'Technology' subdimension, shows that, from a product development perspective, there is a promising potential of infrastructure for battery modularity and battery replacement stations. Aspects that are considered crucial for the implementation of these concepts, such as Big Data Analytics, Decision Support Systems, Cloud Computing etc. are highly ranked. On the other hand, effort still needs to be made to the lower ranked subdimensions for the enablement of this concept's implementation.

7. Conclusions and outlook

The investigation of I4.0 KETs, under the concept of battery modularity and the development of intermediate battery replacement stations, could have high potential on addressing significant barriers, related to the time-consuming battery charging. The particular study focuses on bringing together the modular batteries concept, which is still at a very early stage, with the new concept of intermediate battery replacement stations.

From a product development perspective, modularization correlates with a radical change in the automotive industry. The modular battery pack design and distribution, under the concept of battery swapping stations, could lead to improved network capabilities and to manufacturing mobility. Modularity could be considered as a new milestone in the automotive industry, targeting at the optimization of global production networks and operational flexibility. Latest achievements in the field of complex assembly decision-making and the use of advanced technologies in design under the concept of I4.0, have rendered the necessary feasibility and adaptability possible, towards the implementation of modular concepts in the industrial sector (Remco, Halman, and Hofman 2016).

Nevertheless, several issues and challenges could be raised in the implementation of modular concepts into the automotive industry. Primarily, the distribution of modular battery packs will have a major impact on the vehicle design and the battery manufacturing network. In order for profitability towards standardization to be maintained, a significant effort should be made by the car manufacturers. This leads to the requirement for evaluation of the necessary investments, for adaptation to this concept from the suppliers and manufacturers' perspective, in order for the optimal balance to be obtained between green economy and its impact on industry. From the research side, I4.0 KETs are increasingly adopted in the production phase, particularly in the automotive sector. Despite the high potential of increasing the production's performance, in terms of product quality, production time and cost, the wider implementation of these technologies is still at an early stage. To this effect, significant effort, that could lead to the faster maturation of these technologies and increase reliability, should be made by increasingly evaluating the implementation of such concepts into real applications and scenarios.

Following the requirement of addressing the limited driving range of BEVs, the battery modularity and the use of I4.0 KETs could be a great potential for the employment of novel concepts, based on the implementation of replacing battery intermediate stations, which could be realized through the existing network of gas stations.

In terms of future work, the overall concept of intermediate battery charging stations could be further investigated under the business models of the Product Service Systems (PSS) or the Industrial Product Service Systems (IPSS), as a new service in the EV market.

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