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Systems Engineering Based Sustainability Improvement in Automotive Product Development

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Abstract: Affected by new trends, automobile companies have altered stakeholder requirements on their main product - the automobile. With enactment of new regulations concerning sustainability, new features appeared quickly, such as electrification, sharing services, autonomous mobility and so on. In this study, we present sustainability as a stakeholder and analyze the method of its realization in Systems Engineering (SE) based product development. Formula SAE provides a validated setting to conduct experiments on integrating sustainability into the classical product requirement architectures. By taking into consideration the use of SE or adding other methodological frameworks, findings can establish a new setting in sustainability research. The results of this study may be enlightening for scholars and practitioners and calls for further research on embedding sustainability requirements in automotive product development by using SE.

Keywords: Requirements management; Systems engineering; Sustainability; Automotive product development; Life Cycle Assessment

1. Introduction

As for the complexity of the entire transportation industry, automotive mobility has significant transformations, which are driven mainly by technical innovations, such as autonomous driving, electrification, internet of things, or new legislative standards [1]. Due to digital transformation of automobiles and the whole mobility system, the number of integrated software-based functions has been increasing rapidly [2]. These changes have serious impacts on organizations and urge decision makers to react on product development approaches in order to maintain their competitiveness [3, 4]. The extent of digitalization suggests that one of the key toolsets for re-gaining market positions may come from software industry, in which Systems Engineering (SE) has been applied extensively [5]. Due to specific mindset based on systems thinking, SE can manage complex systems and has been proved to improve project results in new product development [6, 7]. It is a structured methodology, which mainly aims to meet the needs of stakeholders and satisfy their requirements throughout the product development processes [8]. Apart from taking customers and shareholders into consideration among stakeholders, we can identify a number of other entities as such. As for the technological and legislative challenges that automobile companies cope with, we assume that SE application in automotive product development can lead to products, which not only better meet the basic requirements of customers, but also meet the sustainability requirements in all fields more effectively [9].

In this study, we highlight the role of sustainability goal as a legislative stakeholder and analyze the realization of sustainability in requirements architecting processes in a large-scale automotive product development environment, which is called the Formula SAE (FSAE) [10].

2. Methodology

2.1 Sustainability in Automotive Product Development

Nowadays, environmental protection and environmentally conscious lifestyle have attracted a great attention. People attach great importance to how a manufacturer protects the environment during its production process. In the 20th century, the automotive industry mainly focused on increasing the performance of internal combustion engine and trying to increase its efficiency at the same time. When the EURO 1 emission standard was introduced in 1992, the automakers were forced to reduce the pollutant content in automotive exhaust gases. Six generation emission regulations have been enacted since then, which changed measurement cycles [11]. The out-of-date New European Driving Cycle (NEDC) was used till September 2017 and was replaced with Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP), which works with a model and is much closer to the actual driving habits than its predecessor. Apart from this new test procedure, the Real Driving Emissions (RDE) test is introduced [12]. RDE measures vehicle emissions in road traffic with the help of a Portable Emissions Measurement Systems (PEMS), which is attached to the towing hook of the vehicle. This system measures the direct tailpipe emission, but it is not equal to the real emission value, which can be connected to the vehicle. The Life Cycle Assessment (LCA) examines the entire life cycle of a product. From this point of view, we take into consideration every material and energy process concerning the product, instead of the location or time of production. LCA consists of extraction of resources, production, assembly, packaging, transport, use, recycling and disposal [13, 14].

The ISO 14040:2006 and ISO 14044:2006 are applied to the LCA activities. Although LCA is being used in many areas of life, there are further opportunities in the business marketing. According to the life cycle analysis, if a company's products are more environmentally friendly, this can be an advantage compared with its competitors. However, like any assessment system, LCA has limitations with availability and validity of the input data being its greatest weakness. When examining the entire life cycle of a passenger car, we need to look beyond the direct CO_2 (tailpipe) emission. The life cycle of a vehicle can be divided into the following processes:

- Extraction and production: carbon dioxide emitted during the extraction, processing, machining and installation of all raw materials, which are used in the vehicle.
- Well-to-Tank: carbon dioxide emitted during the production, refining, transportation and storage of the fuel or alternative propellant.
- Tank-to-Wheel: carbon dioxide emitted directly by the vehicle. This is the exhaust gas, which is measured during the driving cycles, such as NEDC and WLTP, and can be found on the data plate of the passenger car.
- Recycling and disposal: carbon dioxide released during the recycling of all possible components at the end of the vehicle's life cycle. This includes the disposal of parts, which are not recyclable but contain substances harmful to the environment. In addition, it can contain additional costs and increased emissions of electric car batteries, which are being studied.

None of the processes listed above should be omitted from the life cycle study, or the assessment will show a manipulated and false result. All these processes give an approximate amount of total carbon dioxide emitted during the life cycle of a vehicle, which is illustrated in Figure 1.

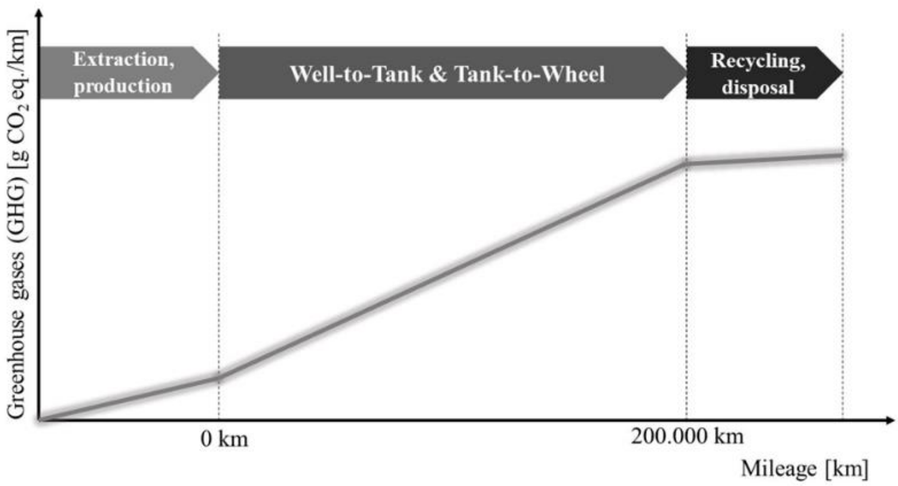

Figure 1. Whole life cycle of a vehicle with 200.000 km mileage

Environmental impact is computed with CO_2 equivalent value (CO_2 eq.) during LCA. This value contains the weighted average of the Greenhouse Gases (GHG). Each harmful gas has a unique multiplier, which shows its relation to the greenhouse effect of carbon dioxide. This is called GWP 100 value, because it shows the Global Warming Potential (GWP) of each compound, assuming that they are present in the atmosphere for 100 years [15].

A question was raised in our previous research: does the LCA methodology cover all possible environmental impacts concerning the given product? The results show that this methodology does not provide reliable results, especially in the field of energy production [16], because it does not take into consideration the interactions between the studied and enclosing systems and the patterns of human psychology and behavior. For example, we have good reason to doubt the actual carbon neutrality of energy production methods, which are classified as renewable in public consciousness. During the operation of renewable energy sources, conventional power plants have to operate in a limited power output, which leads to less efficient energy generation than the nominal working point operation. When the renewables cannot generate electricity, it is necessary to maintain the equivalent amount of capacity from the conventional side to meet the capacity demand. We suggest this aspect and the connecting amount of CO_2 should be taken into consideration during the product development. The other possible additional environmental effect is the human psychology. It appears during the automotive development processes when the automakers develop the most efficient and state-of-the-art vehicle propulsion technologies. The consumed amount of fuel in 100 km stays around 6-7 liters, while the performance is more than 10 times higher [16]. The behavior of the customers is not negligible, because it determines the attributes of the product. In addition, at the end of the supply chain, they are (we are) responsible for establishing a sustainable future. We suggest the current LCA methodology should be combined with the above-said interactions between the enclosing systems and the human psychology, thus determining the real carbon footprint of a product, particularly the automotive development processes. This new methodology is called Multilevel Sustainability.

2.2 Systems Engineering for Sustainability

SE is especially important when considering human factors, such as customer behavior and demand. Biahmou highlights the impacts of sustainability on social, economic and environmental development, and emphasizes the inadequacy of its consideration in product life cycle. This observation legitimates the call for SE as it is envisioned to promote the effective management of customer and legal requirements and preferences of other stakeholders [9]. In addition, the papers also discuss the circumstances of realization of sustainability arrangements in current business models [17, 18], or the consideration of sustainable requirements within or outside the customer requirements [19]. Application of SE is expected to solve these challenges by implementing relevant tools and techniques. When using SE to predict the sustainability impact on product properties, the alignments with social, environmental and economic models should be included [9]. This integration activity is shown in Figure 2.

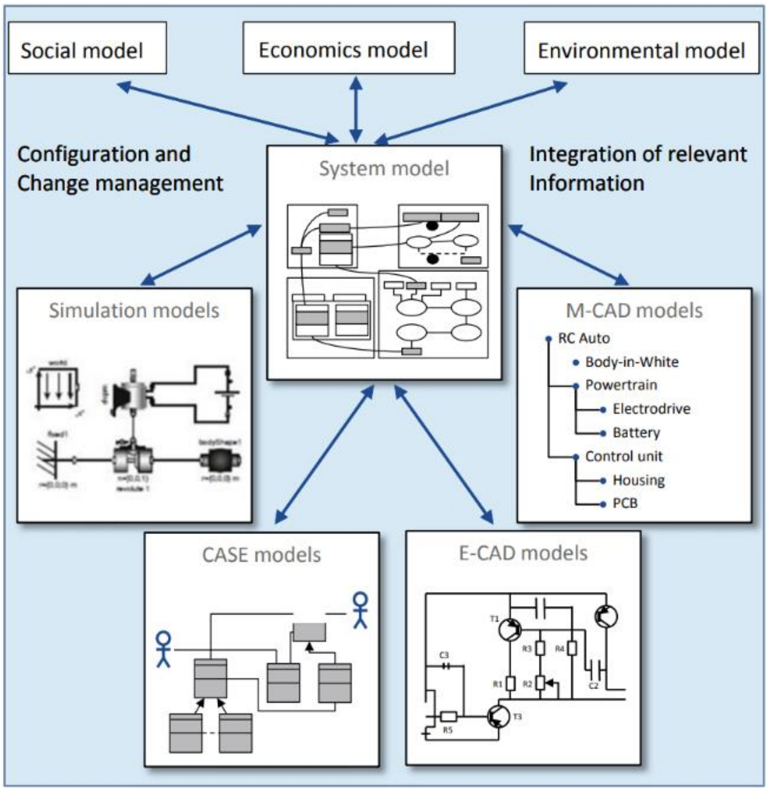

Figure 2. Aligning classical product models with sustainability models [9]

2.3 Requirements Management

A specific framework for product modeling using SE methods is based on Requirement-Functional-Logical-Physical (RFLP) levels [20]. In order to facilitate improvement and validation of all objects and processes, the RFLP approach should be adopted from the highest-level architectural development to the lowest-level technical components [21]. According to Baughey [21], RFLP can be used to improve vehicle concepts to meet somewhat high-level customer requirements. Other literature highlights the role of requirement management, that is stakeholders' preferences to the requirements of the most detailed subordinate system components [22, 23]. Topcu and Mesmer [23] proposed that a primary stakeholder should be defined first, and preferences of other stakeholders had to be combined with it. When designing multifunctional systems, the key importance features include the definition of system-level requirements, functional specifications and architectures, as well as the relation of sub-systems and traceability [24].

2.4 Research Objective

In this research paper we intend to present an approach, which facilitates the SE-based integration of sustainability requirements into the classical requirements set of a vehicle concept. This study is considered as a part of a comprehensive research stream about the implementation of SE in a large-scale automotive product development environment. Sustainability has become a highlighted area, in which stakeholders define their rigorous requirements for industrial product development projects. In addition, sustainability is emphasized and expected in the FSAE, which makes our experiments especially important in the model environment. After reviewing relevant literature in detail, we find that a substantive practice analysis has not been made in the organizational implementation and application of SE-based requirement architectures in automotive product development. We intend to extend the knowledge on prerequisites of product development processes by taking into consideration SE methods and sustainability [9]. Therefore, we seek answers to our research question as follows:

RQ: As a part of a Systems Engineering implementation process in automotive product development, how to take sustainability into consideration and incorporate it into requirement architectures?

2.5 Research Design

In order to provide immediate findings for scholars and practitioners in the automotive product development industry, we initiate a research project within the field of FSAE, and conduct a participatory action research consisting of a range of qualitative research methodologies [25]. In this study, we present the description and outcomes of a training session, which is organized for requirement architectures development. We play the roles of observer and trainer in the training. Table 1 provides a summary of participants, agenda and outcomes of the training.

Table 1. Training participants, agenda and outcomes

PARTICIPANTS	**9 team members**	**Top management plus department leaders**
AGENDA	45 mins	Presentation on background knowledge and examples
	15 mins	Brainstorming on requirements
	45 mins	Development of requirement architectures at the whole vehicle level
	45 mins	Integration of sustainability into whole vehicle requirements
	15 mins	Feedback
OUTCOMES	Recognition of the potential benefits of using RFLP framework in conceptual design	
	Development of a dummy requirement architecture at the whole vehicle level	
	Consideration of sustainability in vehicle design. New set of requirements integrated	
	Core team learned to use SE tools. RFLP framework is ready for application in conceptual design	

During the 165-minute training session, the participating members learned about the possible automotive applications of RFLP architectures. As for architecture benchmarks, we reviewed and utilized the work of Friedenthal et al. [26] in the automotive industry, but we focused on industrial setting. In addition, as indicated in the agenda and outcomes in Table 1, the team developed a sample architecture at the whole vehicle level.

As participants engaged in the development of requirement architectures, constructive discussions and debates started. By using the elements of the architectures, the team members not only discovered correlations between the components, but also established new interdepartmental relations because of fruitful technical arguments. Finally, they agreed to add the elements of the sample requirements tree. In a word, according to individual training evaluations and our primary observations, the overall morale among participants was exceptionally positive and all of them were very active.

Researchers played two roles of trainer and observer in the workshop session. Due to the latter role, all major events and outcomes have been documented in detail, including all critical comments from the participants, attitudes, vibes and team morale. By carefully recording and analyzing numerous useful technical debates, we sorted out our data in order to introduce and explain key results throughout the next section.

3. Results

At the end of the first training session on development and application of requirement architecture, a participant considered it as a "great step forward". When being empowered to develop their own FSAE-specific architecture, the participants took the exercises seriously and accepted the new approach, though it was novel and had more requirements. By taking sustainability into consideration, the architecture made significant transitions in FSAE as well. Electrification and hybrid powertrains had been dominating the whole field and conceptual arrangements towards sustainability were appreciated by the judges.

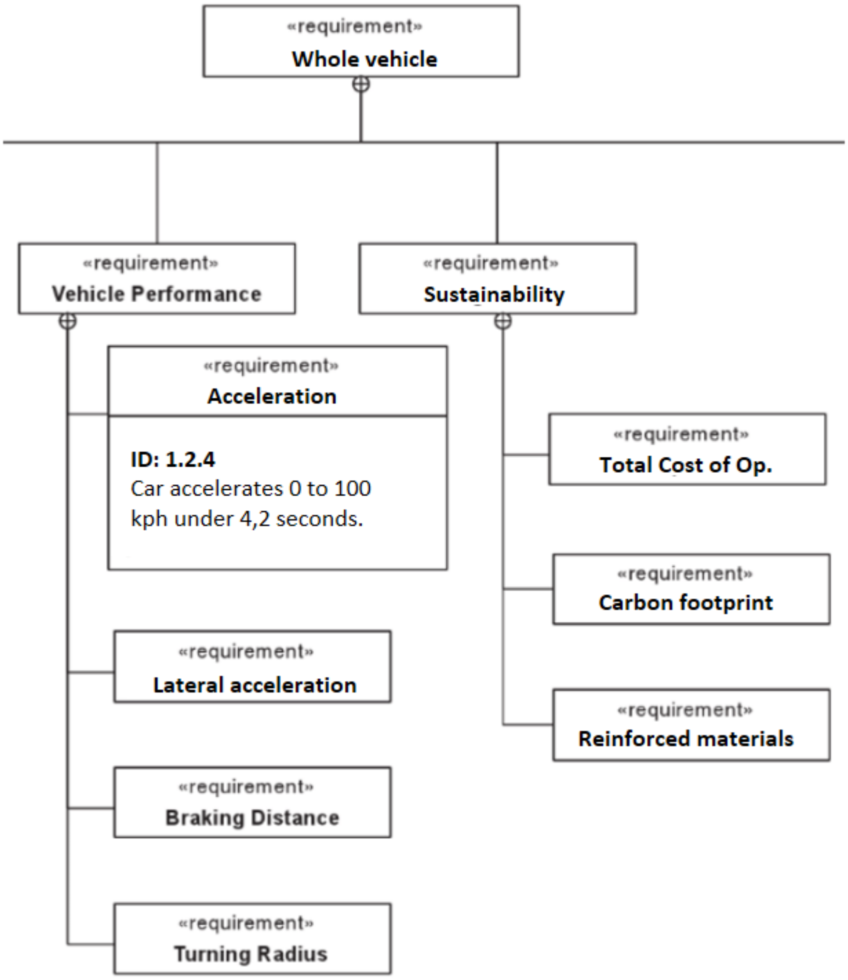

Figure 3. Example for requirement tree design including sustainability aspects

Figure 3 presents an extracted version of the designed requirements architecture, in which sustainability requirements are divided into three sub-groups, namely, use of reinforced materials, e.g. carbon fiber, minimizing the carbon footprint of design and manufacturing activities, and optimizing the total cost of ownership. Two of the sub-groups are environmental and one is economic. (The FSA tree is lacking of the social aspect at the top-level requirements, however this might be considered at subordinate levels.) LCA is the most complex methodology used today to determine the carbon footprint of a product, technology or service. In addition, we have suggested the consideration of Multilevel Sustainability framework [16]. At the end of the training session, more LCA analyses were requested to be arranged into the teamwork.

By considering sustainability as a top-level requirement in Systems Engineering, it opens several possibilities to broaden the lower level requirements. One of the above-said is carbon footprint. Calculation methodology of Greenhouse Gas (GHG) emissions of an FSAE car is very similar to that of a passenger car. All emissions should be taken into consideration throughout lifetime of the car. When studying the requirement environment, we found that, apart from carbon footprint, there was another sustainability-oriented demand concerning the environment, that is, utilization of reinforced materials. Lightweight structures are extensively used in FSAE, and these parts are usually made of carbon-composites. Besides the maximum reliability, one of the engineering goals is to build the lightest car. Therefore, the reinforced lightweight materials have a huge advantage. In addition, we consider these as a possibility to reduce the consumption and emissions of cars. We collected related information to make a comparison between carbon-composite frame and tubular steel frame in accordance with LCA methodology. First, compared with tubular frame, due to use of more rare raw materials and energy intensive production technology, the production of carbon monocoque frame generates additional CO_2 emissions. Second, in both cases, their well-to-tank phase and origin of fuel are the same, and there is no change in the production. In this step, as for a hybrid FSAE car, the CO_2 content of the electricity need to be considered. Due to utilization of reinforced lightweight materials during the operation, the tank-to-wheel emission will reduce. At the end of the life cycle, the relationship between the recycling or disposal of carbon-composite frame and the tubular steel frame needs to be studied.

Considering the framework of the previously discussed Multilevel Sustainability concept, we propose an improved version of traditional LCA analysis. The two aspects of Multilevel Sustainability, enclosing system and human psychology, appear together in our case. Reinforced lightweight materials are used because lower weight is expected to reduce the tank-to-wheel carbon footprint in use. However, the enclosing system and human psychology cannot be neglected. In addition, the FSAE is a motorsport theme competition series and the main goal of all teams is to finish the race the first. For instance, this is the reason why the majority of working points of the engine are wide-open throttle stages. Because a driver will drive smoothly regardless of the frame design, the power output of the engine is the same in both cases, which is the reason why there is no significant change in fuel consumption or emission. The only advantage is better lap times because of high-speed and performance-intensive segments and higher corner top-speeds and in the event of more dynamic acceleration. From this example, we find that there are connections between the top-level requirements in the background and we cannot neglect the utilization of Multilevel Sustainability. Utilization of lightweight materials has positive effects on vehicle performance. But there is no advantage in tank-to-wheel emission and the increased energy and material demand for production causes additional emissions.

4. Discussion

Our analysis aims to reveal the technical feasibility and organizational acceptability of integrating sustainability into a SE-based requirements management system. As a result, we find that the application of a SE-based requirement management system is essential to take into consideration top-level requirements of all stakeholders appropriately and effectively develop technical specifications for the next product design phase.

In conclusion, the effects of empowerment and involvement are prerequisites of winning quickly for a team. Probably the most influential and experienced members of the team participated in the structured training session, which led to successful development of requirement architecture at the whole vehicle level. Implementation of such activities is generally an integral part of teamwork in project development. In addition, sustainability has been taken into consideration, in which environmental and economic sub-preferences are dominant. It seems to modify a number of other sub-systems, such as chassis, vehicle dynamics, powertrain and ergonomics. Sustainability in top-level requirements shows the appearance of stakeholder demands in a new area. Our experiments reveal that an SE-based requirements management process not only facilitates the judgement and classification of subordinate requirement-tree elements, but also provides an applicable view to overcome difficulties in the decision making on specifications.

5. Conclusions

Research outcomes of this article may provide a new in-practice validated look for the analysis of Biahmou, which links SE to sustainability [9]. LCA has been proved to be a great tool to further specify sustainability-oriented requirements, which can be applied in combination with SE. In fact, we confirm the potential benefits of considering sustainability as a top-level requirement (or either as a stakeholder). It should be discussed in a holistic way, and even can be exploited further based on future research results. Integrating sustainability into the stakeholder requirements analysis at a high level proposes a new project of SE utilization. Today, virtual car development appears to be faster and cheaper and achieve better results in some sub-processes of total vehicle development [27]. Spread of advanced simulation tools promotes the extensive development of digital automobile in the whole industry. However, as for sustainability requirements set on the development itself, it is assumed that there is room for improvement. Therefore, partially based on the above-said training outcomes, we mainly study the environmental and economic impact of product development processes. Carbon footprints and costs should be assessed at each dedicated sub-process. Based on the data, the processes can be analyzed and ranked in accordance with their sustainability. The least sustainable processes should be considered to be transformed virtual.

This study has some limitations in terms of its methodology. Although the applied participatory action research provides a great access to in-depth information, the data sample should be extended. In addition, the integration of sustainability requirements needs to be conducted in a more complex manner.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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