System Lifecycle Management: Initial Approach for a Sustainable Product Development Process Based on Methods of Model Based Systems Engineering

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Martin Eigner[1], Thomas Dickopf[1], Hristo Apostolov[1], Patrick Schaefer[1], Karl-Gerhard Faißt[1], Alexander Keßler[1],

[1] Institute for Virtual Product Engineering, University of Kaiserslautern, Germany

[1]thomas.dickopf@mv.uni-kl.de

Abstract. Modeling today's products means modeling interdisciplinary 'product systems' integrating various authoring systems with the technical-administrative product structure and the related processes. Achieving sustainability of the stated product systems brings new artifacts expanding the area to be considered and impedes traceability. This paper introduces System Lifecycle Management as key concept. Along with an approach based on methods of Model Based Systems Engineering the outlined problems are solved on an exemplary sustainable development process. The paper defines the framework for modeling the product system in the early development phases, which accompanies system design considering sustainability aspects in a prospective view. To demonstrate the proposed method, the paper focuses on expanding existing modeling constructs by relevant behavior elements capturing semantic links and information about the usage. First analyses and capabilities of the approach are presented in a case study of a wheeled excavator.

Keywords: System Lifecycle Management, Model Based Systems Engineering, Sustainability, Traceability.

1 Introduction

Contemporary technological products are multi-disciplinary systems developed by multiple engineering disciplines. The risen requirements on these systems led to a complexity explosion, especially with regard to the information flow within the product development process [1]. As a result of new upcoming legislation focusing on sustainability, complexity is increasing furthermore [2]. But, in parallel to the challenges arising, great opportunities are also evolving for manufacturing companies to make their contribution to the sustainability paradigm and to gain advantage over their competitors through ecologically, economically and socially motivated system and process innovations [3] [4]. A multi-disciplinary system development requires a rethinking of common methods, processes, IT solutions and organizational forms as known in product development today. To cope with complexity and to assure fulfillment of new requirements, traceability throughout the entire system lifecycle is needed. Today, traceability in a Product Lifecycle Management [1] [5] solution manifests itself only in relations defined between product requirements and elements of the bill of material.

This paper considers System Lifecycle Management [6] as a key concept for the definition of engineering design processes. Model Based Systems Engineering (MBSE) [6] [7], as essential part of the System Lifecycle Management concept, is a multi-disciplinary engineering paradigm to guide the design process in the early phases and to achieve traceability. In this paper a new approach for a comprehensive system description based on an extended V-Model [8] is presented. It constitutes a promising new instrument for functional system description helping to achieve a multi-disciplinary system development taking into account the environmental aspect of sustainability. The model builds upon work of the ERMA research project [9], which aims at proactive estimation of the eco-performance of future concepts of wheeled excavators.

2 Motivation and Objective

In the field of construction equipment, with well-established, mechanical, hydraulic, hybrid and electronic solutions, the need of eco-design will increase significantly because of further increase of energy costs, stricter energetic requirements and growing competitive pressure. The prospective view within ERMA [9] requires analysis of the wheeled excavator and the application of Life Cycle Assessment [10] [11] in a proactive manner supporting the product development.

Table 1. Key Drivers of Environmental Impact.

Lifecycle Phase	Environmental Impact Parameter
Production	Raw material extraction
	Manufacturing processes
Operation	Usage, Maintenance, Energy consumption
	Replacement of spare parts and fluids
Recycling	Recycling, Disposal,
	Includes all waste from maintenance

Extensive concepts and new structures, such as innovative and integrated technical solutions for increasing the total energy efficiency, are needed [12]. New requirements on the product's sustainability and eco-performance as well as the demand for high flexibility lead to complex product systems which contain mechanic, hydraulic, electric and even hybrid subsystems [13]. Systems like the investigated wheeled excavator are characterized by a large number of constituent parts, complex processes and, referring to the lifecycle, a dominance of the usage phase due to high energy consumption throughout a long lifecycle [14] [15]. The overall effect of energy and resource reduction through new technical concepts is often hard to predict, especially in the case of multi-disciplinary systems. To quantify these predictions is even harder. This leads to the need for a comprehensive system solution [16].

The results shown in *figure 1* are based on the product structure, related manufacturing, transportation and distribution processes as well as an assumption for the usage phase. Regarding the lifecycle of a commercial vehicle more than 90% of the greenhouse gas emissions are resulting from energy consumption out of the usage phase.

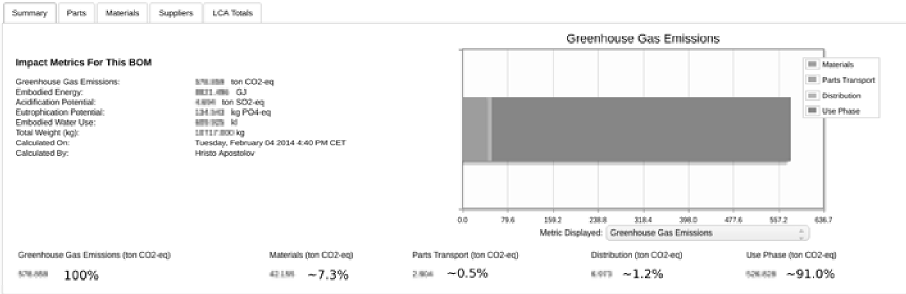

Fig. 1. Environmental Impact (Example: Greenhouse Gas Emission) Regarding the Lifecycle of a Commercial Vehicle (adapted from [17]).

The paper is limited to an exemplary consideration of the usage phase as main driver of the environmental impact. It deals with the outlined problem of an early system description based on a dynamic view referring to specific behavior artifacts using the example of greenhouse gas emissions. Challenges for a sustainable development process are:

(a) Multi-disciplinary View on Complex Product Systems:

Current development processes of complex mechatronic products are heavily influenced by multiple disciplines like mechanic, electronic and informatics as well as dependencies between information elements and engineered system parts. System specification, modeling and first simulations are still discipline-specific.

(b) Lifecycle View on Complex Product Systems:

Beside the assessment of the used materials based on the product structure, a comprehensive consideration of all related processes, starting from raw material extraction to the end-of-life activities as well as all supporting processes like transportation, are of central importance in regard to sustainability.

An approach based on the methods of Model Based Systems Engineering can help to improve the traceability within complex multi-disciplinary systems throughout multiple lifecycle phases and thereby to identify the key areas to be targeted by an exemplary case scenario of the sustainable development process of a product system.

3 Related Work

To enable an early system description the new concept of System Lifecycle Management, with a proposed extension on the V-Model within, is a promising new instrument for functional description of a product system. In order to introduce an approach for exemplary sustainable product development process, the theses that are described in this paper build upon the previous work on sustainability assessment [2] [3] [18] [19] [20] [21] [22] [23] and research on the topic of Model Based Systems Engineering performed at the Institute for Virtual Product Engineering (University of Kaiserslautern, Germany) [24] [25].

3.1 System Lifecycle Management

Up to 80% of the essential characteristics of each system are determined in the early phase of its development [1]. Decisions made here are fundamental for the entire lifecycle of the product system. Revising the system or changing processes in later phases causes great effort. System Lifecycle Management represents a concept rather than a monolithic IT system. Similar to Product Lifecycle Management [3] [5] [19] [22] [26], System Lifecycle Management [6] [27] is an integrated, information-driven concept to improve the performance of a product system over the entire lifecycle. It achieves efficiency by using a shared information core system that helps engineers to efficiently manage complexity in the lifecycle of the product system from first definition of requirements to end-of-life activities. Thus, the concept does not provide innovative systems but can contribute to engineering at administrative level *(see figure 2)* by providing the right information at the right time in the right context.

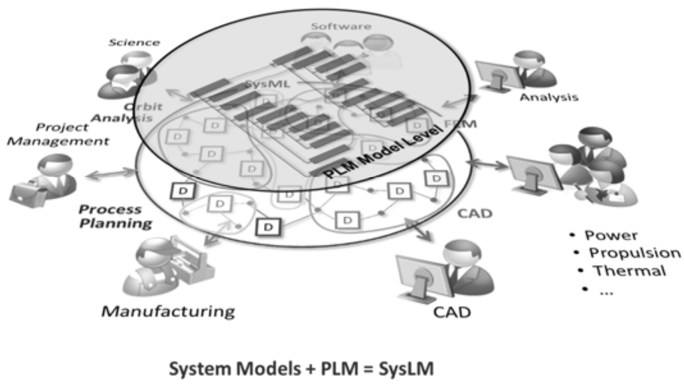

Fig. 2. Two-Layer-Model of System Lifecycle Management (adapted from [6] and [7]).

Definition: System Lifecycle Management (SysLM) is a general information management solution extending today's Product Lifecycle Management to the early phase and all disciplines including services. The concept is based on the direct or indirect (via TDM[1]) integration of various authoring systems along the system lifecycle with the technical-administrative backbone for system or product models and processes. All development phases and the resulting models (R,F,L,P, … [2]) of the system's lifecycle are included and connected to achieve traceability.

As an exemplary extension to Product Lifecycle Management in regard to Eco-Design and sustainability [1] [3] [28] [29] [30], System Lifecycle Management can help to improve the environmental and sustainability performance of a product system by achieving traceability with regard to the material flow, starting from extraction of raw materials, processing, production, manufacturing, storage, transport, usage and disposal. In addition, requirements traceability is realized over the entire development process. Within, the concept of Model Based Systems Engineering provides methods to guide the cross-disciplinary, virtual product development process and to achieve the required traceability.

3.2 Model Based Systems Engineering

Model Based Systems Engineering (MBSE) is a multi-disciplinary engineering paradigm propagating the use of models instead of documents to support analysis, specification, design and verification of the system being developed [31]. Systems Engineering as such, comprises technical but also management processes to generate a balanced system solution in regard to various stakeholder needs and to reduce risks that can hinder the success of a project [32]. In the case of sustainability, this could be an early consideration of the usage phase. In the study introduced in this paper, by using models instead of documents, a discipline-neutral view of the system specification is created. The resulting coherent system model helps to understand and to overview the complexity of the developed system and, moreover, it simplifies the communication in the multi-disciplinary development team. Interdependencies between individual system components are managed; the system is kept consistent to the specification and satisfies all defined requirements. In this context, requirements traceability can be archived over the entire development process. In previous work done at the Institute for Virtual Product Engineering [24] [25], a methodical guideline for the use of the Model Based Systems Engineering paradigm has been developed *(see figure 3)*.

With regard to the V-Model from [8], the extended V-Model enables a model-based and structured system description on the left wing of the 'V' in the early design phases. The systemization on the left wing of the V-Model is used to describe the three levels of specification, first simulation and discipline-specific modeling. Parallel to these overlapping levels, the information artifacts or model elements are

[1] Team Data Management (TDM): Authoring tool-close (local) management system for a development team, regardless of the PLM backbone.

[2] Requirement, Function, Logical System Element, Physical Part, etc. (R, F, L, P, …): Defines information artifacts out of system or product model within the development process.

differentiated in requirements (R), functions (F), logical solution elements (L) and physical parts (P), which are modeled in authoring tools and languages.

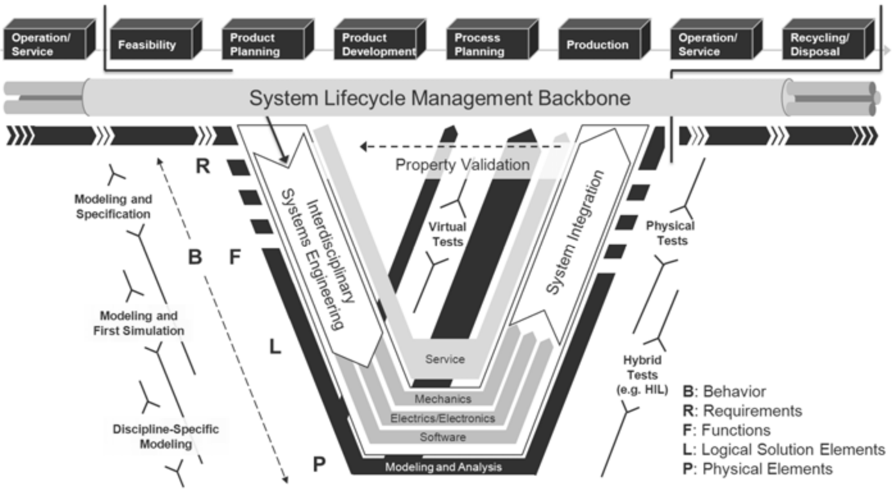

Fig. 3. Extended V-Model for Multi-Disciplinary Product Development (based on VDI 2206 [8], adapted from [24][25]).

Through semantic links between different model elements, as well as between elements of the same type, traceability could be ensured from a 'horizontal' and 'vertical' point of view *(see figure 3)*. 'Vertical' traceability is to be guaranteed by linking system elements hierarchically above different system levels. The allocation links between different model types (R-F-L-P) permit 'horizontal' traceability over the different system specification stages [24]. New in this context is the consideration of behavior (B) within the system development *(see figure 3)*. The behavior of the system and the user's behavior have high impact on the eco-performance regarded.

System models are created by application of the Systems Modeling Language (SysML). In addition, a specific data scheme describes and defines these elements as well as the semantic links between them. Furthermore, it allows integrating and managing the information in a System Lifecycle Management (SysLM) backbone.

4 Approach

Several solutions for sustainability assessment of product systems have been developed [20] [22] [33] [34] but the subject is still not solved satisfactory. None of these solutions considers both of the introduced challenges in one joint and integrated approach. Following, an initial approach for an exemplary sustainable product development process based on methods of Model Based Systems Engineering is introduced.

4.1 Methodology to Include Behavior in the Early Development Phases

The V-Model from VDI 2206 [8] defines a systematic methodology for developing mechatronic systems, but it is not addressing all aspects of model-based design. This gap between requirements engineering and the intellectual model of the product system has been closed by research [6] [7] [24] [25] within the RFLP-approach and the three layers of modeling and specification, specification and first simulation as well as discipline specific modeling on the left wing of the V-Model. However, the V-Model is not suited to model and maintain behavior such as the usage phase of a product system. An approach for the extension of the V-Model is depicted in *figure 3*.

The following steps describe the procedure of modeling behavior in the early design phases:

Step 1 - Identification of Key Drivers Following the RFLP Approach:
In the first step the occurring gap between requirements and physical parts has to be closed. The outcoming traceability of structural elements along RFLP helps to identify the key drivers at an early level of development.

Step 2 - Specification of Behavior Artifacts in the Early Phase:
Corresponding to the 'horizontal' traceability of structural elements in step 1, a 'horizontal' traceability of behavioral artifacts has to be specified, which allows a quantitative consideration of behavior from an abstract view at requirements level to a concrete description on the level of logical elements. Though this, the identified key drivers from step 1 could be observed in the context of their main functions.

Step 3 - Analysis of Behavior Artifacts in the Early Phase:
For a first calculation and simulation of system's behaviors in the early phases of development, it is needful to generate an analysis context who describes the subset of elements that are needed as well as their relationships through constraints and properties.

Step 4 - Requirement Traceability, Verification and Validation:
Based on the previous steps, with the help of specific simulation and calculation tools the developed system model has to be verified and validated against the requirements. The procedure takes place in iterative loops.

Step 5 - Interpretation and Visualization of the Results:
In this step, the interpretation and visualization of the results are carried out. Concrete recommendations for decisions have to be derived from it.

4.2 Case Study: Modeling Behavior in an Exemplary System Model

The specification of the system model by structure elements in the early phase is too coarse for a detailed assessment which can support the engineering eco-design. It is important to take the usage phase into account already in the early design phase and to provide traceability between the requirements of the product *(see figure 4: R-level)* and the product's physical elements *(see figure 4: P-level).* Based on a simple and abstract example for the modification of an environmental constraint, it will be shown how it is possible and helpful to consider the requirements derived from the usage phase of a working machine, or a similar product, already in the early phases of development by using Model Based Systems Engineering.

Problem description: The greenhouse gas emission for a working machine, e.g. in Japan, should be lowered to a maximum average value of 1.000 t CO_2-eq. (based on the results of *figure 1* in our example we limit the accruement of the greenhouse gas emission on only the usage phase).

Step 1 – Identification of Key Drivers Following the RFLP Approach:

At the example of changed requirement on the allowed average CO2-equivalent emissions of the machine, the traceability provided by the presented approach will help to identify the engine, for example, as a key driver at the logical system level. Figure 4 describes the context schematically.

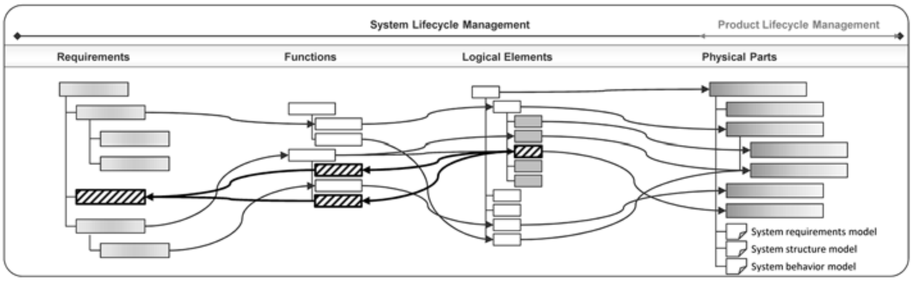

Fig. 4. Schematic Representation of the Identification of Key Drivers through the Traceability along RFLP (adapted from [24]).

Step 2 - Specification of Behavior Artifacts in the Early Phase:

Since the engine as an assembly is not of big importance for the environmental impact, rather a quantitative consideration of working behavior, energy consumption and thereof resulting emissions has to be taken as a basis. The mainly used functionalities have to be modeled at the beginning of the specification and to be considered in dependence of the design of the machine for the specific market. The Systems Modeling Language (SysML) allows describing these major functions in an abstract way with the help of the Use Case Diagram. It illustrate how the system is used to achieve the goals set by its users and with what elements it interacts during operation. These could be people, other systems or the environment [31]. Based on the example of the wheeled excavator *(see Chapter 2),* the lower right part of *figure 5* shows the main use case scenarios according to the test methods for energy consumption of hydraulic excavators [35] modeled in SysML. One possible way to define these use case scenarios in SysML is to associate them with activities in a block context including relevant properties as parameter elements [36].

Activities in SysML describe behaviors performed by specific parts of a system or their components over the entire lifecycle [31]. The relations between different model elements *(see figure 5)* in the system are described through allocation relationships. In regard to the further use of the defined parameter properties, it is important to differentiate their types in the SysML model. The parameter properties might be based on a specification (such as a limitation through a requirement) or on a prediction (such as results from simulations or conclusions from field data).

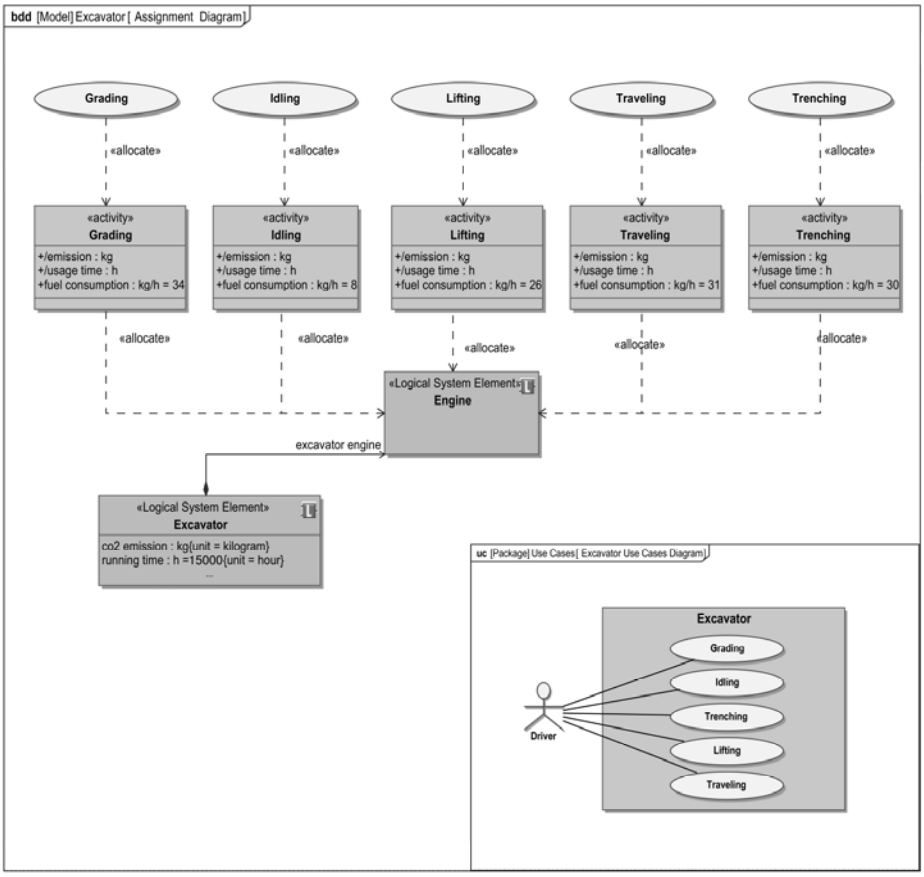

Fig. 5. Setting of Use Cases and their Parameters Referring to Logical Solution Elements.

In the considered situation of usage cycles of a wheeled excavator, a running time of 15.000 hours is supposed to be a specification property as well as a new limitation rate for a greenhouse gas emission lower than 1.000 t CO_2-eq. A prediction property is represented in this case by the simulated value.

Step 3 - Analysis of Behavior Artifacts in the Early Phase:

To simulate or calculate the emission values of the different use cases or, respectively, the emission of the whole wheeled excavator in regard to its usage, SysML allows generating a first specification of a simulation through different diagrams. With the help of a Block Definition Diagram it is possible to determine the context of an analysis *(see figure 6).* Blocks of the system which are utilized in this context are linked to the analysis block by associations. These blocks provide the parameters that are used for the analysis and a placeholder for prediction properties which represent the outcoming results. The current calculation is described by different constraints. These constraints are connected to the analysis context element through a composite association.

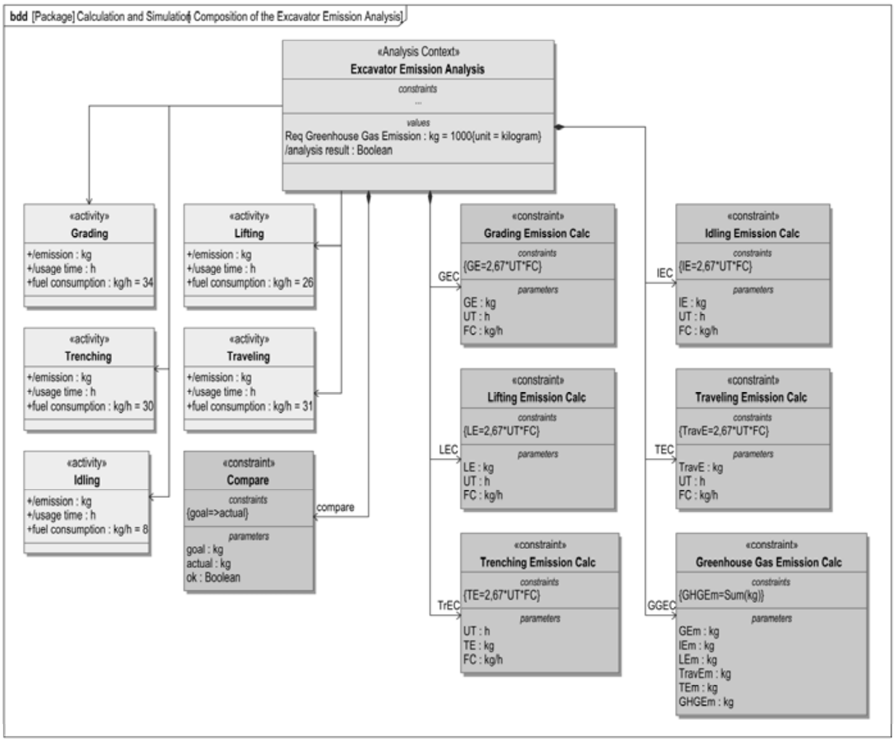

Fig. 6. Definition of an Analysis Context for the Greenhouse Gas Emission of a Wheeled Excavator.

With the help of the SysML parametric diagram the relationship between the different model elements of the analysis context can be described through their parameters and specified constraints [36]. *Figure 7* clarifies the mathematical progression for the calculation of the greenhouse gas emissions of the whole wheeled excavator, as well as separately for the different use case scenarios. Additionally the constraint block 'Compare' checks if the current value satisfies the given requirement. Based on the information of this diagram and the structural system description, test cases can be generated and executed by specific calculation and simulation tools.

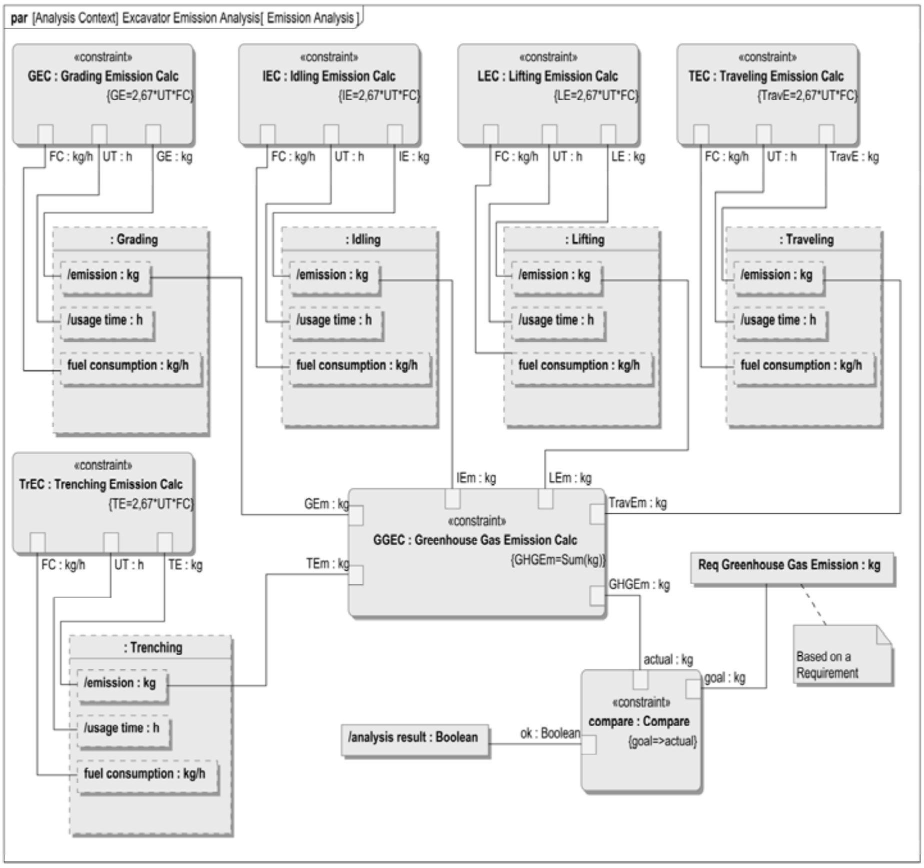

Fig. 7. Parameter Relations for the Analysis of Greenhouse Gas Emission.

Step 4 - Requirement Traceability, Verification and Validation:

In the current example, a need for action on the system's L-level can result from the changed requirement on the average CO_2-eq. emissions and the engine has been tracked down as main driver of the impact. We now consider the machine's behavior over its lifetime *(see Table 2)* assuming (in reality this would be known) the following localized working-cycle distribution:

Table 2. Exemplary Working Cycle Distribution of an Excavator (according to [35]).

Working Cycle	Grading	Trenching	Lifting	Traveling	Idling
Percent of life time	25%	25%	10%	17%	23%
Fuel consumption, kg/h	34	30	26	31	8

Arising from a machine lifetime of 15.000 hours of operating service the following values for greenhouse gas emission as shown in *Table 3* are the results of this calculation.

Table 3. Results from the Calculation in Different Working Cycles

Working Cycle	Grading	Trenching	Lifting	Traveling	Idling
CO2-eq. Emission	340,4 t	300,4 t	104,1 t	211,2 t	73,7 t
Total			1029,3 t		

In regard to the result and with the help of the SysML model it is possible to trace the value to concrete components, functional and logical elements and thereby realize most suitable fields of action. Furthermore new requirements based on this specific working cycles could be added.

Step 5 - Interpretation and Visualization of the Results:
In the current example and based on the results the implementation of a start-stop system for reduction of the time spent in idling would bring a necessary improvement (or optimizing the drive train would be a better option) or one will have to move to the F-level and look for alternative concepts.

Table 3. Variation referring to the Calculation in Different Working Cycles

Working Cycle	Grading	Trenching	Lifting	Traveling	Idling
Life time in hours	3.750	3.750	1.500	2.550	1.050
CO2-eq. Emission	340,4 t	300,4 t	104,1 t	211,2 t	22,4 t
Total			978,5 t		

Last but not least, this information has to be visualized in an easy to interpret way and supplied to decision-makers. An appropriate integration of the proposed behavior artifacts and of a general behavior description into the System Lifecycle Management backbone is part of further research.

5. Conclusion and Outlook

Modeling a complex product system requires the integration of various authoring systems and the product structure with related processes. Following this way, full traceability can be achieved. The paper introduced System Lifecycle Management as key concept integrating the introduced two layers. The proposed approach which is based on methods of Model Based Systems Engineering addresses exemplarily one specific outlined problem of a sustainable development process of a product system. The paper reuses and adapts existing modeling constructs for capturing relevant behavior artifacts at the example of the usage phase of a wheeled excavator. Semantic links are formalized between early definition phase and first prediction in the form of constraint blocks regarding sustainable product development. For the future, the implementation of the introduced approach will be provided within a System Lifecycle Management backbone. To give the user the capabilities to easily trace the impact of design decisions, an intuitive and graphically rich user interface will be implemented on top of the System Lifecycle Management backbone.

Acknowledgments. The authors would like to acknowledge funding from the German Bundesministerium für Bildung und Forschung attended by PTKA for research of mecPro^2 and from Stiftung Rheinland-Pfalz für Innovation for research of ERMA. The authors would like to thank Torsten Gilz and Radoslav Zafirov for their contribution and research on the topic of Model Based Systems Engineering, for their input and assistance.

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