EFFICIENT APPLICATION OF MBSE USING REFERENCE MODELS: A PGE CASE STUDY

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Abstract

Product engineering has become more and more complex, as there are multiple interrelated elements with high dynamic and variance. To support the work of designers and managers, various methodologies have been proposed in the literature. In this paper, it shall be evaluated how the reuse of information stored in reference models can improve the approach of model-based systems engineering to add value in the design process. Therefore a case study is conducted in the battery development department of the AVL List GmbH. A detailed and quantified evaluation of problems caused by complexity is used to derive specific solutions based on the usage of reference models in a model-based approach. Through this approach a reduction of unnecessary effort by 60 % is estimated showing how the usage of reference models adds value in the design process and is a relevant foundation of methodology development.

Keywords: Systems Engineering (SE), Product modelling / models, Product Generation Engineering, Design methodology, Case study

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1 INTRODUCTION

In October last year, Samsung stopped the sales of their prestigious smartphone Galaxy Note 7, as they could not determine the cause of the ignitions of the batteries. The president of Samsung's information technology division in the U.S. stated that the Note 7 had more features than any other phone and that it became uncontrollable with so much innovation. Samsung now has to bear the costs of the recall and the loss of customer trust. Their shares fell more than 8% (Chen and Sang-Hun, 2016).

This case shows impressively the challenge of modern product development which has been stated in the literature already (Haberfellner, 2012): rising complexity. But how to deal with it? One approach is model-based systems engineering (MBSE) with the goal to enable the product development process to be more efficient through a consistent description of all system elements and their interactions (Crisp, 2007). This approach spreads only gradually in engineering practice (Tazir, 2011). The acceptance of a method can be increased if the subjective benefit exceeds the subjective effort. If the benefits and efforts are balanced, the usage of a method can be maintained by supervision (Sauter, 2012).

Comparable numbers concerning the benefit of MBSE can hardly be found. One example is a 68% reduction in specification defects since MBSE practices have been introduced (Saunders, 2011). A study by Delligatti confirms that, on the one hand, an overall benefit can be reached: it quantifies that the number of defects is decreased by one half when utilizing MBSE. On the other hand, the total number of man hours rises when comparing the relative costs (Delligatti et al., 2014).

To handle complexity through a broad usage of MBSE efficiently, the effort in terms of the application needs to be reduced and the benefits for engineers need to be increased. Furthermore, a quantitative additional value to convince managers shall be evaluated to motivate them to maintain the usage.

In this study this is reached by evaluating the implications of complexity in product development, including the consequent usage of reference models in a MBSE-process to match these implications and by measuring how much this approach is able to reduce the effects of the implications.

2 STATE OF THE ART

2.1 Fundamentals of product generation engineering

In the classic methodology of design according to Pahl and Beitz, engineering projects can be divided into new design, adaption design and variant design (Pahl et al., 2013). It is criticised in younger literature (Eckert et al., 2010) that the most common way of product engineering is the improvement of existing products to reduce risk. Therefore, Albers and Bursac exceed the definition of separation of engineering projects by taking approaches from innovation management into account to formalize the "product generation engineering" (PGE) as a field of study (Albers et al., 2015). The PGE describes that the development of a system and its subsystems is always based on at least one reference system and can be divided into three activities: carry-over variation, embodiment variation, and principle variation. These activities take different shares in the development of a new product generation. In order to reduce risk and increase customer satisfaction, the shares of new development should be limited and targeted to customer needs. PGE describes that the consideration of reference products is a basic property of engineering processes. The approach is therefore valuable for method development.

2.2 Fundamentals of model-based systems engineering

Model-based systems engineering as defined by Estefan: "MBSE is about elevating models in the systems engineering (SE) process to a central and governing role in the specification, design, integration, validation and operation of a system. For many organizations, this is a paradigm shift from traditional document-based and acquisition lifecycle model approaches" (Estefan, 2007).

MBSE therefore demands a central model, in which all information can be stored, the "single source of truth" (Eigner, 2014). This approach shall enable the aim of SE to understand, improve or create complex systems by a holistic consideration (Haberfellner, 2012). Furthermore, MBSE enables the recognition of all interactions between the system and its environment and the characterization of system elements and its relations with a model (Winzer, 2013). Stachowiak differentiates and characterizes a model by three characteristic features: every model is an image or a pattern, every model reduces and every model is created to a designated use (Stachowiak, 1973). These attributes lead to a dilemma of reduction: since a model is reduced for a specific purpose, it can hardly be used for a different intent. Therefore, abstract and independent reference models in the sense of product generation engineering are needed to facilitate a consistent description (Albers et al., 2014a). In the context of MBSE, the pragmatic feature of the model is to describe the system elements of the system to be developed with its interactions in a way that is understandable for all involved developers.

3 METHODOLOGY OF RESEARCH

3.1 Research Hypotheses and Questions

New approaches for the descriptions of systems are necessary to handle the increasing complexity. The state of the art provides methods such as MBSE and states that the utilization of reference products is a relevant property of engineering processes. Therefore it should be conducted how a consequent usage of the PGE approach justifies the effort of implementation and usage of MBSE over several product generations. To make a contribution to that, this paper examines the following hypothesis:

The usage of MBSE creates measurable value in the product generation engineering process if the information from reference product models is presented according to stakeholder needs.

To confirm this hypothesis, it will be proceeded according to the design research methodology (DRM) (Blessing and Chakrabarti, 2009). Based on the literature review the following questions are formulated and will be answered through findings of the different studies.

- What problems in concrete development process occur in complex projects of product generation engineering? Descriptive study I, Section 4.
- How do information from a descriptive product model need to be prepared to reduce the risk described by the first descriptive study? Prescriptive study, Section 5.
- What is the added value of this preparation of information? Preliminary descriptive study II, Section 6.

3.2 Research environment

The research design in this thesis is chosen to be an explorative approach, since only a very small amount of knowledge about the central aspect of the research question is available. The concrete situation in an organisation is evaluated to generally deduce applicable statements. The requirements for information processing and the applicability of the solution are only evaluable in real development environments as this will be the target group.

The environment chosen is the process of traction battery development at AVL List GmbH (AVL). In this organisation, a global network of developers specialized on the battery system provide development services in powertrain development. This team consists of various different departments, each dealing with single process steps. Every development team is formed by diversely trained and highly educated experts (e.g. mechanical and electrical engineers). These experts are located at various different locations and therefore deal with different cultural and educational backgrounds.

The complexity in the field of battery development requires a high degree of individual specification on the one hand and simultaneously competence in the handling of interdisciplinary topics on the other hand. AVL is very experienced in complex development processes and several methods and tools e.g. for project management and technical simulations have already been developed.

The organisation has detailed experience in the usage of MBSE in several different fields of powertrain development. The organisation is acquainted with the methodology and the further development is based on already established knowledge.

Therefore, AVL is very advanced in design methods and processes. Striving for continuous improvement, the organisation aims on a research to evaluate how MBSE-approaches can add value. Methods developed in this qualified setting have a high potential to be relevant for other environments.

AVL does not only develop complete systems in successive generations for one customer but also provides engineering solutions in various design steps for different customers. To describe this in terms of product generation engineering they develop various systems with the same type of components with large shares in embodiment- and principle variation to meet different customer requirements.

4 EFFECT OF COMPLEXITY IN PRODUCT DEVELOPMENT

An evaluation of the problems caused by complexity in product generation engineering shall answer the first research question and evince potential scenarios for a possible use of MBSE. Evan though the AVL

can draw on experience from various projects with international customers, rising complexity can force them to invest additional effort of time and money ensuring perfectly aligned solutions. With in-depth knowledge and detailed experience in design methods, those unnecessary efforts are sought to be eliminated with a continuous and consistent improvement process and philosophy at AVL.
Therefore, a detailed specification of the potential negative effects shall be used to adapt risk mitigation methods. Consequently, this study enables a quantification of the benefits of a utilization of MBSE.

4.1 Design of the study

For the execution of the study the format of a process failure mode and effects analysis (pFMEA) has been chosen. The benefit of this format is the already existing in-depth knowledge and acceptance of this methodology (although mainly used in the form of a design FMEA) in the analysed environment.
To conduct the first steps of the pFMEA, interviews have helped to get an overview of potential failure modes and effects. In a further study, the identified failure modes are evaluated and assessed by the means of a self-administered survey to validate and quantify them by a larger sample group.

4.1.1 Process FMEA

The FMEA is a formalized analytical method to identify all the potential failures of a product or process. The aim is to recognize possible capabilities of a design or a process in time to preventively avoid failures. Depending on the time of application and the type of the analysed object, FMEAs can generally be divided into process and design FMEAs (Brüggemann and Bremer, 2015). The objective is to compare the criticality (risk priority number, RPN) of all identified potential failure modes. This establishes the priority for corrective action. Therefore, this analysis can demonstrate the organisation where its resources should be applied (Goetsch and Davis, 2014).
When the pFMEA is introduced in the field of battery development, it is split up into three major parts, which can be considered to be analogous to the method described in literature (Reif, 2014): In a first descriptive study, interviews take place to establish modes and effects of failures. Secondly the RPN is evaluated in a self-administered survey. The measures to overcome analysed failures are elaborated in Section 5. The further assessment of the implemented measures is evaluated in the second descriptive study in Section 6.

4.1.2 Interviews

The reason for conducting interviews in the research environment is to identify potential losses in efficiency still occurring in the development processes of complex systems. This gives a detailed insight of potential use cases for the implementation of MBSE. To maintain as many different answers as possible, and give every interview partner the possibility to steer the interview into different directions, the form of an interview with open answers is chosen. 15 interview partners with different roles from project leaders to engineers from different domains are selected to contribute their insight knowledge on the process of battery development to the evaluation.
Further, the questions for the interview are formulated as follows. Here, the obvious aim is to fill the pFMEA in terms of failure modes and effects:

"Where do you still see potential losses in efficiency in your daily work?"
"What effect does this have on your daily work?"

4.1.3 Self-administered survey

The risk priority number (RPN) is evaluated in a self-administered survey. With this anonymous survey, a higher number of stakeholder shall be attained. The reason for conducting this survey is to evaluate all named failures and assess their significance on the process of battery development. All scenarios have precise and briefly described failure modes, and the same effect: unnecessary effort arises. This enables a very simple and comprehensible evaluation of all stated failure modes in the survey. For instance, a scenario is formulated as followed:

Potential unnecessary effort arises, because tasks are not formulated sufficiently.

To quantify a scenario, the classical RPN has been assessed and adapted to the needs of a retrospective view: the severity is expressed in unnecessary additional effort to deal with the named scenario. This effort can be expressed in both money and time (e.g.: the time to find information or the costs to repeat a validation process). Furthermore, the probability of occurrence is reshaped to the frequency of occurrence per year. It is hence rated how often the named scenario comes into force on average. The definition of the probability of detection is not considered to be necessary in this retrospective view.

4.2 Results

4.2.1 Interviews

The response in all conducted interviews is very helpful to establish a better understanding of the research environment and to provide a basis for the economic evaluation. 193 potential failure modes with failure effects have been assessed in the interviews. In the stated failures and especially effects of failures, many interview partners come up with very similar scenarios. This is a result of the same working environment of all interview partners and shows the urgency of some potential failures. Due to similarities they are clustered into 24 scenarios (see Table 1) and evaluated and validated in the survey.

4.2.2 Survey

The survey is answered by various different stakeholders such as project managers or system engineers in order to fulfil the necessary diversity of the respondents. The frequency and severity of all 24 scenarios is evaluated in the survey to calculate all risk levels. With an internal, nonlinear key, it is possible to translate the risk level into a potential monetary negative value per average project and year. The most important results of the total potential loss per year and per project are displayed in Table 1 in percentages. The percentages emphasize the result of one scenario when compared to the other scenarios. The number does not indicate how many percent of a project are evaluated to be potential for improvement. Table 1 shows the 7 highest rated results. Hereby the description of the arising effort is based on the interviews, the percentage pictures the share of the calculated effort compared to the other scenarios.

Table 1. Selected results of the survey

Unnecessary effort can arise, because…	**Percentage**
…already gained knowledge from previous projects (Lessons Learned) is not being used.	24.03 %
…it is not clear at the project start, which requirements are not or only insufficiently feasible.	12.97 %
…overall project objectives are not sufficiently defined, coordinated, and accessible.	7.42 %
…tasks are not formulated sufficiently.	5.87 %
…necessary information from past projects are not accessible.	5.92 %
…project documents are stored on different locations and/or several times.	5.43 %
…deliverables are not sufficiently specified or tailored to customer needs.	5.52 %

4.3 Conclusion of the evaluation of failures

This two-step evaluation of the potentials in the process of battery development highlights and evaluates very comprehensively different scenarios of potential unnecessary effort. Even though only a small number of the established scenarios is validated in the survey, it is shown that most scenarios are rated to likely have a very strong negative impact on the daily work process.

The concrete and quantified scenarios provide an approach to derive requirements for the definition of the work environment. The evaluated scenarios show how the increasing complexity can affect the development process and involved stakeholder economically.

Furthermore, this descriptive study and especially the scenario rated with the highest risk level highlights the importance of risk mitigation using e.g. the approach of product generation engineering.

5 ADRESSING THE SCENARIOS THROUGH MBSE

How do information from a descriptive product model need to be prepared to reduce the risk described by the first descriptive study? The second research question will be answered in this section. Therefore, several creativity workshops in cooperation with the target group have been carried out to create and refine solutions how a model needs to be integrated in the engineering process.

5.1 Clustering of requirements

Each scenario can be understood as a requirement for the usage of MBSE, as the utilization shall solve the problem stated in the scenario. During the analyzation of all scenarios, it is recognized that the measures regarding the top three scenarios also enable the reduction of several other scenarios. Therefore these measures each form a cluster of scenarios, which they address. The share of unnecessary effort of the single scenarios is summed to the "Cluster %" (Table 2).

Table 2. Clusters derived from the top scenarios

Unnecessary effort can arise, because…	Scenario %	Cluster	Cluster %
…already gained knowledge from previous projects (Lessons Learned) is not being used.	24.03 %	Reuse of Information	40.08 %
…it is not clear at the project start which requirements are not or only insufficiently feasible.	12.97 %	Requirements management	22.28 %
…overall project objectives are not sufficiently defined, coordinated, and accessible.	7.42 %	Generic deliverables in a process model	19.59 %
Other			18.05 %

Cluster 1 - Reuse of information

Knowledge management is playing a significant role in today's product development. The resource knowledge forms an intangible asset of the intellectual capital of an organization. A tool for handling knowledge and individual information shall create measurable value in a sustainable manner. (North and Kumta, 2014) The survey underlines the necessity of a fully working, easy to comprehend, and always available tool to manage knowledge. The top scenario: "…already gained knowledge from previous projects (Lessons Learned) is not being used" can be generalized to the reuse, availability, and findability of information. In this way, the first cluster "Reuse of Information" is formed, which in total accounts for 40.08 %.

Cluster 2 - Requirements management

Handling requirements is a significant reason for possible project failures as described by RUPP. The majority of mistakes happens in the phase of analysis at the beginning of product development (Rupp, 2012). The highest potential unnecessary effort "it is not clear at the project start which requirements are not or only insufficiently feasible" targets a future-oriented view. Along with the other scenarios about distribution and traceability of requirements, the second cluster "Requirements Management" is formed, which in total accounts for 22.28 % of the potential unnecessary effort.

Cluster 3 - Generic deliverables in a process model

The third cluster of potentials describes the absence of coordination of objectives with customers and the translation into tasks. Final deliverables are the added value a customer pays for (Siyam et al., 2015). Therefore, those deliverables need to be coordinated in the best possible way and the information shall internally be available to every employee. A process model, as part of project management, shall enable the benefit of more accurate offers to the customer or more precise task description for single employees (Hirzel, 2013). Along with other scenarios about specification and distribution of tasks, the third cluster "Generic deliverables as process model" is formed, which in total accounts for 19.59 %.

The three clusters cover over 80% of the total effort and will be addressed with a set of measures, designed in the prescriptive study.

5.2 Implementation of MBSE with a generic reference model

A model in the context of MBSE is a central point of access and structured place for storing cross-linked information. This could enable to overcome the stated problems. Also, the access to information generated in other or past projects is necessary for the success. This accessibility can be generated by a generic model. A generic model contains all previously built models and further information (such as data from benchmark-studies) and therefore all relevant functions and components with all interactions and context information. Based on this generic model, a product model for the current product development process can be derived. It is the task of product development to generate a physical structure based on the system reference model (see Figure 1).

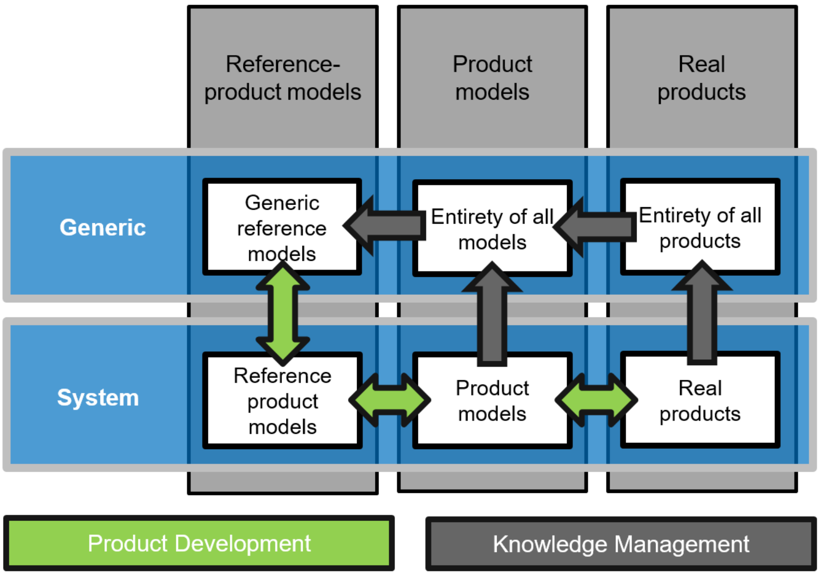

Figure 1. Cycle of knowledge management and product development in the framework of the levels of abstraction in systems modelling (Albers et al., 2014b)

The generic reference model contains in this context all logical system elements that ever occurred in any product generation in a generic description and their relations. That means functions and types of requirements, components, stakeholder, and in order to address the requirements for Cluster 3 tasks and deliverables are included forming a process model. For example, "lithium-ion cell". Linked to the logical elements are the specific instances of them such as "lithium-ion cell Type 1". The relations between those elements describe which interaction occurred between model elements already. This generic reference model learns and grows with every modelled specific system and every benchmark study (see dark arrows in Figure 1). For more details see Albers et al. (2014b). To build such a model existing different descriptive models need to be analysed and combined. The departments have to agree on wording and occurring relations.
A reference product model can be extracted, according to the requirements of a project, containing all relevant information and only the relevant elements. In the design process, this reference model is transferred to a model of the physical specific structure of the system describing the real product. This procedure can be performed on system and on process side and is refined in the following list to address the unnecessary effort identified in Section 4.

5.3 Brief overview of the specific measures

Cluster 1 - Reuse of information

- Elements of information, which are not included in the model, can be addressed by the model as central point of access.
- Elements of information can be generated by Lessons Learned (for instance in the form of a FMEA or textual) or by benchmark programs.
- The model offers a consistent structure and assigns coordinated terms which are understood by all involved stakeholder. This can be supported by a term management system for synonyms. There are, for instance different names used by different departments or customers for the same component (e.g.: Housing and casing).
- Information can be attached to model elements (functions, components, requirements, and tasks) and therefore be recovered and accessed easily.
- Combinations of model elements (such as task A and function B) narrows down and facilitates the search for specific information.

Cluster 2 - Requirements engineering

- Specific customer requirements are connected to the generic requirements in the model. This is possible for all new requirements requested by the customer, which only changes in terms of the value but not in terms of the principle function.
- Critical requirements can be identified by the model:
  - By the comparison with already specified requirements it can be assessed if the requirement is targeting for the organisation unknown values (for instance a very high voltage).
  - Due to the connection in the generic model, value ranges of interacting requirements can be assessed according to new combinations.
  - New requirements that have never been processed up to today can be identified.
- The connection of requirements to responsible stakeholder (in previous and current projects) simplifies the allocation of responsibilities and fosters the collection of already generated information.

Cluster 3 - Generic deliverables in a process model

- Detailed definition of the deliverables during a sales process prior to project start.
- The generic reference model contains the milestones with pre-set required deliverables and their brake down to specific task outputs is accessible. These deliverables can be refined and expanded with the customer.
- The time and cost calculation to achieve these deliverables can be trained to improve calculations, by a connection between objectives and deliverables in the process model with the product model. Linked top-level objectives, as defined by AVL internally, are displayed and adaptable
- A clear objective of the precise description and connection of certain objectives in the battery model enables the representation of dependencies: For instance, cost are increasing when efficiency is being emphasized. These can be adapted concerning current customer needs.
- Further, agreed on customer objectives are the start for a new product model, based on the generic battery model. Therefore, all discussed and fixed objectives are always available during the project.

6 EVALUATION OF THE APPROACH

This section contains the second descriptive study of the DRM to answer the question "What added value does this preparation of information have?"

6.1 Research design of the second descriptive study

An FMEA requires a new evaluation of the RPNs to quantify the effect of a measure. Due to cost reasons, the questioning only lasts one hour for a limited number of participants. It has included the explanation of the approach and therefore the FMEA procedure. To facilitate the evaluation, a basis of the given RPN without the installed measure is assumed. Each participant shall then evaluate to what extent the measure may reduce the described problem (Table 3):

Table 3. Design of the survey to evaluate the effects of the measures

	This measure reduces the effort by				
Scenarios	100%	75%	50%	25%	0%
scenario 1					

Participants

The target group contains a number of employees who have been part of the first interrogation already. To discuss the topic in detail they are invited to several one hour workshops in small groups. Eight employees have participated and answered the survey completely. The participants represent various parts of the engineering team and the sample group can therefore be considered representative.

6.2 Results of the evaluation of the approach

After averaging the results of every scenario and weighting them over the risk levels, the participants estimate a reduction of the preliminarily evaluated unnecessary effort by 60%. The discussion and the comments indicate that the 40% of left effort may be traced back to effort occurring through the

utilization itself and effort caused by actually missing information which is not available at a certain point of time.
The biggest risk is identified to be the inconsequent usage of all involved stakeholder and tools, which can only be overcome with a highly sophisticated and to a very high extend prefilled generic reference model including entities of the process and the product battery system.
The definition of the structure and the initial filling of the generic reference model has been executed by AVL in a highly complex process lasting 3 years and involving all necessary experts in terms of battery development. Today the everyday implementation in current customer projects trains and improves this generic model. This know-how and the readiness for continuous improvement together with all customers enables a deep understanding in the methodology concerning product development for the organisation today.

7 DISCUSSION AND OUTLOOK

7.1 Discussion

The study has shown that unnecessary efforts arising in complex product development projects can be reduced by 60% through the usage of MBSE with the consequent consideration of reference models, supporting the hypothesis of this paper. The feedback from the evaluation workshops also suggests, that the approach has a great potential to reach user acceptance as the subjective benefit exceeds the effort. The adapted FMEA approach also shows a way to quantify the organizational benefits.
It has to be considered that the study has been carried out in an example engineering department with specific characteristics (Section 3.2). To underline the hypothesis, the surveys shall be implemented in a larger environment and in different settings. In these further studies, the scenarios that define the outcome of the survey should be validated due to their relevance as they originate from error-prone expert questionings.
An improvement is estimated due to the study involving the previously described participants with their expert knowledge concerning the use case only. The actual improvement can only be measured after an implementation (Sheard and Miller, 2000).

7.2 Outlook

AVL strengthens its MBSE knowledge and the development of batteries even further by implementing this approach in pilot customer projects. Therefore, a software tool on the basis of the generic reference model is developed. First the measures for cluster three shall be ready for test applications and a return on investment for the implementation is estimated in two years after the end of this study. The improvement will be monitored in accompanying research over the next years to further adapt the method and to continuously improve the development processes. The AVL can offer their process knowledge to improve the design processes for their customers.
Part of this study have also been the proposal of the front end of a software tool that visualises the information provided by the models and a preliminary transfer study, which contains a teaching concept in workshop character. The results of these studies will be elaborated and published separately.
The elaboration of this approach can contribute in future research to the handling of complexity and may therefore prevent incidents such as the burning battery cells of Samsung's smartphones described in the introduction.
The increased acceptance and the expectations of a return on investment through the implementation of MBSE, which could be achieved by taking the PGE into account, lead to the suggestion that the integration of the PGE-approach for other method development should be extended.

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