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Identification of requirements of methods and processes for modeling objectives in predevelopment projects

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Abstract

Today's predevelopment projects have complex and dynamic objectives. Hence, methodology and tools must adapt to this. This is achieved through documentation and explanation of goals, constraints and requirements and their interrelations, which the members of the engineering team and individual decision-makers are aware of. This is followed by recurrent discussions and consensuses thereof which enables them to work together more efficiently as roles, tasks and responsibilities are unambiguously defined and effectively as it enables the team to alter a set of objectives in specific aspects and to track progress efficiently. The transfer of the results of existing research in modeling objectives into professional settings is rather difficult and requires methodical support. The requirements for tools, methods and processes to model objectives in predevelopment projects are unclear. Therefore, the perceived added value of existing approaches and tools is too small which leads to restraint in the industry.
This research effort identifies requirements for methods and processes to model objectives in predevelopment projects. On that basis, the identified requirements are evaluated regarding their importance. Afterwards, existing methods are summarized and categorized.
This is done by means of a systematic literature review and studies based on a predevelopment project with a duration of half a year. 41 graduate students in seven teams develop seven products and showcase their concepts in several prototypes with guidance of methodology experts. Engineers of an industry partner and a research facility review the current results and progress and decide the further course of action in milestones. This research consists of expert interviews, surveys and consulting of the engineering teams.

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1. Motivation

Literature shows that development processes require a comprehensible model of objectives. This is especially true in predevelopment projects, as it eases the transfer of a predevelopment project to a development project or to another department. A prerequisite for this is the unambiguous definition of relevant objectives. Previously uninvolved individuals require comprehensible objectives to assess the attainment of objectives correctly. Various processes and methods, hereafter referred to as approaches, are currently used in series development to address the issue of communicating or managing objectives. This paper focuses on the management of objectives in predevelopment which differs greatly from series development [1]. Predevelopment projects are characterized by at least partly unknown and frequently changing objectives and interfaces of the system in development (SiD). Furthermore, relevant stakeholders are partly unknown, the use by customers cannot be demonstrated [2] and functionality as well as financial viability and technical feasibility are to be proven [3]. Predevelopment projects aim to provide a functioning prototype to demonstrate the concept [2]. The requirements of approaches for modeling objectives of predevelopment projects are unknown. Therefore, existing approaches are not designed to satisfy the specific needs of predevelopment projects.

In this paper, these requirements are elicited by an initial literature review, that is then discussed and complemented in expert interviews. Afterwards, a second literature review is

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performed to further elicit and categorize the elicited requirements. Finally, the requirements are ranked regarding their importance in a quantitative survey. This will enable the substantiated modification of existing approaches to improve the chance success of predevelopment projects.

2. State of the art

2.1. Knowledge management

Knowledge management is a core aspect of the product engineering process (PEP) [4,5]. Knowledge is the combination of experience and information in context, and the interpretation and reflection thereof [6]. To deal with short development lead times and the need to supply unique solutions while adjusting to changing requirements, it is crucial to acquire, organize and link knowledge [7–9]. This is done in a knowledge base. Transfer of knowledge and the reuse of information such as lessons learned, best practices, objectives of past projects tends to fail without proper knowledge management [10].

2.2. Systems engineering and requirements engineering

Systems engineering is an interdisciplinary approach that identifies interrelations between subsystems of a SiD and disciplines involved in the PEP [11]. Systems engineering deals with the whole system and coordinates cooperation of experts [12] throughout the whole PEP. It relies on an iterative top-down process to design, develop and operate a usable system [13].

Oftentimes, predevelopment projects start with a somewhat vague set of objectives [2]. Development projects require a much higher level of concreteness of objectives. It is the system engineer's responsibility to attain this level of detail. This means approaches to model objectives must support the system engineer from the initiation throughout all phases until the transfer of the predevelopment project. Approaches that comply with this are referred to as continuous.

To ensure the success of a SiD systems engineering utilizes requirements engineering. Requirements engineering focuses on provider and customer needs, demands and the required functionality of a product [14].

Specifications of complex engineering processes must be easily adaptable to necessary technical modifications and altered functional and performance requirements. Therefore, a fixed definition of requirements, e.g. in a task clarification [15] or requirement setting [16], is no longer sufficient [17,18].

2.3. Model of objectives

The model of objectives consists of goals, requirements and constraints, hereafter referred to as objectives, and their interrelations [19–21]. Changing team members of the engineering team, different customers and decision makers require a consistent modeling approach to ensure that all stakeholders related to the SiD have the same understanding. This is especially true for stakeholders outside the actual PEP, as it is the case for OEMs that are increasingly transferring responsibility for SiDs to their suppliers [22]. Objectives are defined based on the synthesis of knowledge items of the knowledge base [20].

It is crucial to identify conflicting objectives [23] and to prioritize among them or resolve the conflicts since the scope of solutions is defined by the model of objectives [24]. Any model of objectives is an information system [25]. Hence, the modeling of objectives is similar to an information system development (ISD) [26]. This means requirements of approaches for information system development are relevant for approaches to modeling objectives.

2.4. Validation

Validation is a core activity of the PEP [20] as it is the basis for a purposive PEP. Validation is the confirmation based on objective evidence that a system is suitable for its intended purpose [27,28]. Verification refers to the confirmation that specified requirements are met [27,28]. With regard to product engineering, validation means confirmation that the objectives align with the purpose of the SiD and that the model of objectives is consistent in itself. Verification refers to the assessment of the attainment of validated objectives [29]. Thus, validation is a continuous activity throughout the PEP ensuring that the correct objectives are attainable, and that attainment of objectives is measurable. This is done by comparing the actual progress with the planned progress [20].

3. Methodology and approach

Predevelopment projects are aiming to test, develop and incorporate new solution principles with limited resources. This implies a high level of variation of the SiD [2]. To ease the transfer to series development it is necessary to elicit relevant requirements and to make them comprehensible to all members of the product engineering team.

There are many approaches for modeling objectives. The needs of a continuous approach for modeling objectives of predevelopment projects are unknown. Therefore, existing approaches are not designed to meet these [25,30]. This is especially true for the involvement of experts in the elicitation and validation of objectives by the system engineer. This highlights the need to identify the requirements of approaches to model and organize objectives in predevelopment projects. In this paper the following research questions are answered:

- What are general requirements that approaches to model objective have to comply with?
- What are the requirements of experts of product engineering for approaches to model objectives of predevelopment projects?
- How can these requirements be categorized?
- How do engineers prioritize the requirements for approaches to model objectives?
- What approaches do exist that support the modeling of objectives of development projects?
- How do existing approaches comply with the identified requirements?

This research effort provides a clustered list of requirements for approaches to model objectives in predevelopment projects. This is followed by an overview of approaches that are currently used to manage objectives in the product engineering process (PEP) and a short evaluation of the types of approaches based on the identified requirements.

The requirements are compiled based on an initial literature review followed by interviews with nine engineers from two different sites (subsidiary A, B) of the same well-known machinery manufacturer. At least four engineers of each subsidiary participated in the separate, semi-structured interviews with duration of 45 minutes each. The engineers of each particular subsidiary represent a homogeneous group. The engineers hold different positions in product and project management. All engineers have worked for at least five years in product development at the large machinery manufacturer.

The findings of the initial literature review are discussed in the expert interviews. This is used to assess the significance of the elicited requirements. Afterwards, a second literature review is performed which details the requirements with high relevance for predevelopment. The elicited requirements are clustered based on the interviews and the literature reviews.

Next, a survey among the participants of the predevelopment project "IP – Integrated Product Development" is conducted to prioritize the requirements. The predevelopment project IP has a duration of six months. It is a course for graduate students in collaboration with an industrial partner [31]. The application process for IP involves a formal application, an assessment center, workshops and a screening process in which relevant skills and experiences, such as methodical knowledge and problem-solving skills, are identified. IP involves 41 selected graduate students organized in seven teams and two mentors of an industrial partner and one mentor of a research institute per team as well as several more experts to support decision-making on milestones. The mentors of the industrial partner work closely with their engineering team for instance by validating and eliciting objectives.

A third literature review is used to identify and categorize approaches used in development projects of which at least fragments elicit, organize, validate or asses attainment of objectives. This third literature review is necessary since there is little overlap between literature on requirements of development projects and literature about approaches used in today's development.

In a final step the properties of the clusters of approaches are then compared with the identified requirements for modeling objectives in predevelopment projects.

4. Results

4.1. Requirements of approaches for modeling objectives in predevelopment identified in the initial literature review

The initial literature review yielded the following requirements:

- effort-benefit ratio as combination of effort [32,33] and total benefit [19]
- short-term benefit [32]
- complexity [34]
- customizability and adaptability with regard to boundary conditions e.g. organizational structure [32,35]
- suitability for corporate culture [35]
- comprehensibility [19]
- traceability [19]
- flexibility, effort for minor changes [33]
- simplification of communication and consensus building [33]
- support of the identification of objectives [33,36]
- simplicity of the approach [33,36]
- availability of training opportunities [36]

4.2. Discussion of the requirements of approaches to model objectives in predevelopment identified in the initial literature review

The interviews with engineers showed similarities but also disagreements between both subsidiaries which indicates slightly different company cultures. The interviewees agreed on the importance of:

- total benefit
- effort-benefit ratio
- uniform standard
- comprehensibility
- ease of consensus building and communication
- unambiguous communication structure and responsibilities
- purpose of approach is clear to user
- flexibility

Experts of subsidiary A stress their lack of time to use and learn a time-consuming approach. They would not use an approach that doesn't prove beneficial in the project it is used at no matter the long-term benefits. Experts of subsidiary B do not agree. They emphasize long-term benefits and are willing to accept additional effort in the short-term.

4.3. Categorization of requirements for approaches to model objectives

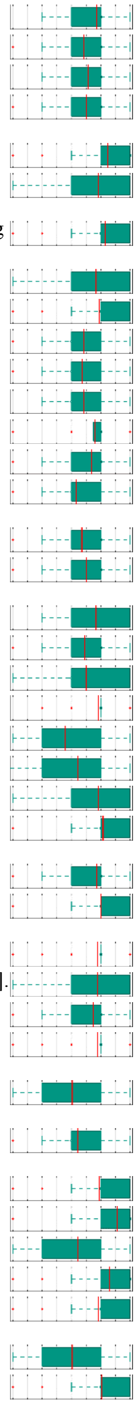
The second literature review is performed based on the findings of the initial literature review and the interviews. It yielded a comprehensive list of 40 requirements listed in Table 1. During this process some of the requirements are rephrased. The requirements are organized in the following five main clusters, derived from the categories used by Posner [37] and Keller and Binz [38,39] :

- Stability describes the robustness of an approach towards subjective and situational influences.
- Transparency refers to the comprehensibility of the structure and the results of an approach.
- Structure describes the ability of different stakeholders to structure and control objectives.
- Adaptability refers to the ability of an approach to adapt to different situations and boundary conditions.
- Usefulness refers to the added value of the approach regarding limited time, effectiveness and efficiency.

In this paper effectivity in product engineering is understood as pursuing the proper objectives. Efficiency refers to the resources needed to attain a specific objective [32,40].

Table 1. Prioritization of requirements for modeling objectives.

requirement cluster super cluster	sub-cluster	#	requirement	weight 1 2 3 4 5
stability	reliability	1	Different people must obtain the same result and must be able to understand each other's results.	
		2	Multiple repetitions of the approach must yield the same results [37].	
		3	The approach must always produce a useful output no matter the input [37].	
	objectivity	4	The subjectivity of users of the approach must not influence the quality of the model of objectives to a significant degree [37].	
transparency	comprehensibility	5	The overall purpose of the approach for modeling objectives must be easy to understand [19,37,41,42].	
	learnability	6	It must be easy to learn and train the use of the approach to model objectives e.g. through workshops, webinars and case studies [37,43].	
		7	The approach and structure must be unambiguous so that the user is less prone to errors and monitoring the model of objectives is simplified [42].	
	usability	8	Engineers and other stakeholders must be able to use and adapt the approach as needed [37].	
	transferability of knowledge	9	The approach must support the transfer of knowledge between projects and stakeholders [41].	
structure	traceability	10	The origin and change history of the model of objectives must be traceable [42].	
		11	The approach must allow for an assessment of maturity of specific objectives [43,44].	
		12	The approach must allow various stakeholders to track relevant objectives [43].	
	reduces complexity	13	The approach must support structuring of objectives [37,45].	
		14	The approach must support systematic clustering of objectives [37,46].	
	granularity	15	The approaches must provide consistent levels of refinement of the model of objectives corresponding to stakeholder needs [42].	
	controllability	16	The approach must allow for monitoring and controlling of the modeling process of objectives.	
		17	The process of approving objectives and their maturity (especially regarding the status fulfilled) must be strict and prevent the bypassing of gates.	
adaptability	compatibility	18	The approach must be compatible to various products and various levels of innovation.	
		19	The approach must be compatible to various organizational structures [35].	
		20	The approach must be compatible to various personality types and cultures [32].	
		21	The approach must support interdisciplinary collaboration on the modeling of objectives [43].	
	flexibility	22	The user must be able and allowed to skip steps of the approach [37].	
		23	Iterative repetition of a step or fragment of the approach must be possible [37].	
	integrability	24	It must be possible to integrate the approach into several design approaches [42].	
usefulness	extensibility	25	The approach must allow for simple and fast integration of altered objectives, requirements and constraints [42,47].	
	effectiveness	26	The approach must support the identification of interrelations between objectives [43,47].	
		27	The approach must provide a usable visualization of objectives and the interrelations between objectives [37].	
		28	The approach must provide an objective base for decision-making and consensus building.	
		29	The approach must support the synthesis and analysis of technical solutions and their reasoning [48,49].	
		30	The approach must enable the evaluation and validation of objectives [50].	
		31	The user must be able to assess how much time is required to obtain a model of objectives with a sufficient quality by using the approach [37].	
		32	The approach must result in a model of objectives that can be compared to other model of objectives [50].	
		33	The approach must provide means to assess the quality of the model of objectives and specific objectives [37,43].	
		34	The approach must support the identification of objectives [33,36,37].	
		35	The approach must prove beneficial in the project it is used at.	
	efficiency	36	Modeling objectives must require minimal time invest.	
		37	The approach must have an adequate effort-benefit ratio [33,37,42].	
		38	The approach must give the user the impression to be efficient and thus gives incentive for further use [37].	
	tools	39	The approach must not require expensive software [42].	
		40	The approach must not require complicated software tools, instead the software tools should be intuitive to use [42].	



4.4. Prioritization of requirements of approaches for modeling objectives

The structured requirements are used in a quantitative survey among graduate students of IP. 38 of 41 participants completed the survey. All requirements are evaluated regarding their priority on a 5-point scale. The scale is: not important (1), rather unimportant (2), rather important (3), important (4) and crucial (5).

The results of the survey are shown in the last column of Table 1. In this column a boxplot ranging from 1 to 5 is displayed. The average is marked by the red line.

Table 2. Selection of approaches to model objectives.

type	name	description
meta-model	V-Model (VDI 2206)[28]	• generic procedure for developing mechatronic systems. • includes the steps: definition of requirements, system design, domain-specific design, system integration, assurance of properties and modeling of the SiD
	VDI 2221[51]	• describes a general methodology for the development of technical systems. • describes engineering activities and in which phase they have to be performed
	Münchener Produkt-konkretisierungsmodell (MKM)[44,52,53]	• framework to categorize activities and results of PE based on the concreteness of the product models. • focuses on characteristics of product models and highlights the interrelations between the scopes of solutions and of requirements.
	3-Cycles-Model of product development [49,54]	• the PEP is based on the interaction of the cycles strategic product planning, product development and development of the production systems. • highlights the iterative character of the product engineering process (PEP)
	integrated Product engineering Modell (iPeM)[55–57]	• holistic framework to record and support product engineering and management activities based on the systems triple • integrates various approaches and methods.
phase models	Stage-Gate-Process[58–60]	• widely used model to plan and control the entire PEP. • the ideal process consists of individual phases separated by gates that are used to assess the degree of fulfillment of requirements, as well as adherence to schedules and budgets.
	Spiral Process[61,62]	• the spiral process originates from software development and focuses on planned iterations. • all phases performed multiple times, which continuously increases the product maturity.
methods to organize objectives	system requirement / specification VDI/VDE 3694 [63–67]	• specification sheet: compilation of all requirements of the customer with regard to delivery and performance parameters. • system requirements define the means by which requirements of the customer are to be realized.
	Product data management (PDM)[68]	• stores and administrates all data related to a specific product including meta data. • current information can be displayed automatically, additionally all past iterations can be accessed.
	MBSE[69]	• model-based systems engineering (MBSE) is a formalized approach to model system requirements and verification and validation activities.
	Requirements Engineering[70]	• subset of systems engineering • it involves all life-cycle activities devoted to identification, analysis, documentation and validation of requirements, as well as processes that support these activities.
	Systems Triple [18,71]	• contains all relevant targets and the corresponding boundary conditions, dependencies and relationships.
methods to validate objectives	QFD / House of Quality[16,72,73]	• method to elicit and define customer's requirements and demands • identification of quantifiable engineering characteristics • optimization of quality, which is a function of engineering characteristics corresponding with the satisfaction of customer demands and needs
	FMEA[66,74]	• methodical approach to identify potential failure modes, their causes and to evaluate and prioritize the corresponding risk or criticality. • aims to increase reliability and safety of the SiD before it is used by customers
	RAMS[75]	• RAMS (reliability, availability, maintainability, supportability) aims to objectify decisions regarding reliability.
methods to prioritize objectives	Objectives Tree Method[16]	• states objectives unambiguously by utilizing a diagrammatic form (e.g. tree diagram) to organize and relate objectives hierarchical. • organizes objectives into super- and sub-objectives.
	Function Analysis Method[16]	• each objective is rephrased as function and classified by input and output. • black box diagram is used to identify and visualize interrelations among objectives and impacted components
	FURPS+[76]	• classifies relevant requirements into the main categories' functionality, usability, reliability, performance and supportability.
	Weighted Objectives Method[16]	• weighting of objectives based on impact on key characteristics and properties of the SiD • evaluation of engineering designs based on the degree of fulfillment of an objective and its weight
PSP	Münchener Vorgehensmodell (MVM)[77]	• problem-solving process (PSP) that is based on the three main steps clarification of goals or problems, generating alternative solutions and decisions-making. • non-linear structure to encourage iterations.
	SPALTEN[78]	• linear problem-solving process • focuses on situation analysis and problem identification

4.5. Approaches for modeling objectives

The third literature review is used to compile a list of approaches to model objectives currently used in engineering processes based on VDI 2222 [79,80], VDI 2223 [81] and standard literature of product engineering [15,48,77]. The approaches are listed in Table 2 and clustered based on their purpose. During expert interviews the engineers emphasized the use of approaches to weight objectives other than that the expert interviews could not be used to add approaches for modeling objectives since the interviewed experts are only familiar with few approaches.

4.6. Evaluation of clusters of approaches

Approaches of Table 2 are evaluated in clusters according to the ten most significant requirements. The ten most significant requirements are comprehensibility (#5), unambiguous structure (#7), transferability of knowledge (#9), interdisciplinary collaboration (#21), extensibility (#25), visualization (#27), identification of objectives (#34), short-term benefit (#35), effort-benefit ratio (#37) and intuitive tools (#40). Only clear violations or fulfilment of requirements by a cluster of approaches are mentioned.

All clustered approaches are comprehensible and support interdisciplinary collaboration on modelling of objectives. However, all clusters excluding problem solving processes do not allow for a simple and fast integration of altered or new objectives (extensibility). Problem-solving processes lack an unambiguous structure and visualization of objectives. Clusters of approaches that are unambiguously structured are phase models and methods to validate and prioritize objectives. Methods to organize and validate objectives are suitable for the identification of objectives.

5. Discussion

Transparency, usefulness and adaptability are the most important requirement clusters for managing objectives in predevelopment projects. The most important requirements coincide with findings from previous studies regarding short-term-benefit, effort-benefit ratio, adaptability, learnability and comprehensibility [19,32,33,36]. However, requirements that are not considered significantly relevant in literature are transferability of knowledge, extensibility of the model of objectives as well as its visualization. These are specific for modelling objectives in predevelopment projects. Predevelopment projects require a systematic to have a high level of extensibility as objectives change frequently.

While some approaches, such as MBSE [69], address the issue of visualization only problem-solving processes allow for fast and simple integration of altered or new objectives (extensibility). Problem-solving processes are not suitable to manage and control a complete predevelopment project as they are designed to address a single issue.

Transferability of knowledge is not adequately supported by any of the considered approaches. Especially, regarding the linkage between objectives and the knowledge base which serves as substantiation of the corresponding objectives.

In this research, knowledge is gained about the challenges of modeling objectives in predevelopment, meaning the process between the problem definition and proof-of-concept through a functional prototype. In predevelopment projects various needs of the system engineer can be satisfied by different existing approaches, but never all of them. For instance, FMEA can be used to validate the attainment of objectives. However, the model of objectives must have a certain level of maturity [82]. The system specification organizes many highly detailed objectives as needed in legally binding documents. However, it lacks visualization and is not suitable to transfer “functional and performance requirements” [17]. This hinders communication and discussion of objectives in interdisciplinary teams which is an obstacle to the identification of objectives as well as consistent modeling of the system of objectives. Currently there are no continuous approaches for predevelopment that addequatly support the system engineer. The system engineer lacks support in coordinating experts, linking objectives to the knowledge base as well as in the identification of objectives and their interrelations. Therefore, current approaches are not designed according to the requirements to model objectives in predevelopment projects and thus are not a perfect fit for predevelopment projects. A possible solution to this dilemma is to combine several fragments of existing approaches in one systematic. A systematic is the combination of one or more methods which are integrated in one process. The process indicates certain methods to be used for specific steps based on the phase of the PEP, external input, insights from tests, prototyping, expert consultation, etc.

In addition, the modeling of objectives must be improved as objectives depend on the continuously growing knowledge base and the generated results throughout the PEP. Due to the uniqueness of predevelopment projects, the systematic must be highly flexible. The requirements identified in this research contribution, support the process of method engineering according to the needs in predevelopment projects.

6. Outlook

Further research regarding the requirements for the communication of objectives is necessary. Well-communicated objectives are easier to comprehend which benefits validation and verification of objectives. For this purpose, expert interviews, live-labs and case studies in industrial projects should be used to identify communication barriers in the PEP.

In the next step, a systematic that meets the requirements of predevelopment projects should be engineered. This might be achieved through the combination of several fragments of existing methods. Method engineering provides guidance and tools to implement such a systematic. This will ease the transfer of the SiD to series development, since the transfer benefits from the identification and validation of objectives and their interrelations. This requires linking objectives to the knowledge base and thereby making all objectives comprehensible to all members of the PEP.

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