Forschungsberichte

IPEK
Institut für Produktentwicklung
am KIT ▪ o. Prof. Dr.-Ing. Dr. h.c. A. Albers

Sabine Muschik

Development of Systems of Objectives in Early Product Engineering

Entwicklung von Zielsystemen in der frühen Produktentstehung

Band 50

Systeme ▪ Methoden ▪ Prozesse

Hrsg.: o. Prof. Dr.-Ing. Dr. h.c. A. Albers

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Development of Systems of Objectives in Early Product Engineering

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Dissertation

von

Dipl.-Ing. Sabine Muschik
aus Stuttgart

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University of Cambridge / UK

Vorwort des Herausgebers

Wissen ist einer der entscheidenden Faktoren in den Volkswirtschaften unserer Zeit. Der Unternehmenserfolg wird in der Zukunft mehr denn je davon abhängen, wie schnell ein Unternehmen neues Wissen aufnehmen, zugänglich machen und verwerten kann. Die Aufgabe eines Universitätsinstitutes ist es, hier einen wesentlichen Beitrag zu leisten. In den Forschungsarbeiten wird ständig Wissen generiert. Dieses kann aber nur wirksam und für die Gemeinschaft nutzbar werden, wenn es in geeigneter Form kommuniziert wird. Diese Schriftenreihe dient als eine Plattform zum Transfer und macht damit das Wissenspotenzial aus aktuellen Forschungsarbeiten am IPEK Institut für Produktentwicklung Karlsruhe (ehemals: Institut für Maschinenkonstruktionslehre und Kraftfahrzeugbau) verfügbar.

Die Forschungsfelder des Institutes sind die methodische Entwicklung und das Entwicklungsmanagement, die rechnergestützte Optimierung von hochbelasteten Strukturen und Systemen, die Antriebstechnik mit einem Schwerpunkt auf den Gebieten Antriebsstrang-Engineering und Tribologie von Lager- und Funktionsreibsystemen, die Mikrosystemtechnik mit dem Focus auf die zugehörigen Entwicklungsprozesse sowie die Mechatronik. Die Forschungsberichte werden aus allen diesen Gebieten Beiträge zur wissenschaftlichen Fortentwicklung des Wissens und der zugehörigen Anwendung – sowohl den auf diesen Gebieten tätigen Forschern als auch ganz besonders der anwendenden Industrie – zur Verfügung stellen. Ziel ist es, qualifizierte Beiträge zum Produktentwicklungsprozess zu leisten.

Albert Albers

Vorwort zu Band 50

Sowohl im Maschinenbau als auch im Fahrzeugbau zeichnen sich die Produkte durch eine zunehmende Komplexität und Kompliziertheit aus. Immer neue Funktionen und Funktionalitäten, insbesondere auch im Zusammenwirken von Mechanik, Elektronik und Informatik zu mechatronischen Lösungen können als Verursacher dieses Megatrends gelten. Die Entwicklungsmethoden und Entwicklungsprozesse zur Unterstützung solcher komplexer Entwicklungsaufgaben kommen in großen Bereichen diesem Trend nicht nach. Gerade in der täglichen Praxis der Unternehmen besteht ein hoher Bedarf an methodischer Unterstützung in den Produktentstehungsprozessen. Viele im akademischen Umfeld erstellten Ansätze und Lösungskonzepte haben dabei, insbesondere bei der Übertragung auf die Komplexität der realen Probleme in den Unternehmen große Schwächen. An akademischen einfachen Beispielen entwickelt, sind sie oft nicht in der Lage, die tatsächliche Komplexität und Kompliziertheit realer Entwicklungsprozesse abzubilden. Ein wichtiger Aspekt in der Forschung an modernen Entwicklungsmethoden kommt daher auch der Analyse praktischer Entwicklungsprozesse im industriellen Umfeld zu. Nur durch eine stringente Analyse dieser realen Randbedingungen kann die darauf aufbauende Forschung ihre Relevanz für die praktische Umsetzung von Anfang an beinhalten.

Eine besondere Herausforderung im Bereich der Automobilindustrie, aber auch im Maschinenbau, stellt die frühe Produktdefinition dar, oft auch als „frühe Phase der Produktentwicklung" beschrieben. Der Begriff „frühe Phase der Produktentwicklung" ist dabei leider wenig klar definiert und in vielen Bereichen der wissenschaftlichen Arbeiten auch nicht wirklich durchdrungen. So kann als frühe Phase eines Gesamtentwicklungsprojektes in der Automobilindustrie die erstmalige Darstellung von Konzeptfahrzeugen gelten. Dies beinhaltet dabei schon einen vollständigen Produktentwicklungsprozess inklusive einer Ausgestaltung der technischen Lösung in Form von ersten Prototypen. Die oftmals in der Wissenschaft vertretene Vorstellung, dass man hier die durch funktional orientierte, maximal auf konzeptionelle Lösungen zielende Phase der Produktentwicklung als „frühe Phase" bezeichnet, ist für die Praxis nicht nachvollziehbar. Nur im Kontext der jeweiligen Produktgruppe ist sie überhaupt definierbar.

Die frühe Phase ist gekennzeichnet durch die Produktsuche sowie durch einen hohen Grad an Unsicherheiten in Randbedingungen und Annahmen im Zielsystem. Für den Bereich der Automobilentwicklung ist es von hoher Bedeutung, in diesen Fahrzeugdefinitionsphasen und richtig verstandenen frühen Phasen bereits Methoden und Vorgehensweisen zu haben um Zielsysteme für zukünftige Fahrzeuge möglichst gut auf zukünftige Bedürfnisse abstimmen und definieren zu können.

An dieser Stelle setzt die Arbeit von Frau Dr.-Ing. Sabine Muschik an. Sie hat sich zum Ziel gesetzt, die frühe Phase der Produktentwicklung im Automobil-Entwicklungsprozess methodisch bei einem Automobilhersteller zu untersuchen und auf der Basis der Erkenntnisse neue Konzepte und Ansätze für den Entwicklungsprozess zu erarbeiten. Eingeordnet sind diese Arbeiten in der Forschung am Produktentstehungsprozessmodel iPeM der „Karlsruher Schule“.

Mai, 2011 Albert Albers

Preface of Volume 50

Products in both machine construction and motor vehicle construction are characterised by increasing complexity and intricacy. More and more new functions and functionalities can be seen as cause of this development, especially regarding the interaction of mechanical, electronic and information engineering towards mechatronic solutions. Engineering methods and processes for supporting such complex development tasks are however to a huge extent not keeping up with this mega-trend. Especially in daily work of companies there is a great need for methodological support in product engineering processes. Many approaches and solution concepts put forward in the academic environment have great weaknesses in coping with the complexity of real problems when applied in industry. Developed using simple, academic examples, they are often not able to depict the factual complexity and intricacy of real engineering processes. An important aspect in research on modern engineering methods is therefore the analysis of practical engineering processes in the industrial environment. Only by conducting a stringent analysis of these real boundary conditions, research building on these conditions may keep its relevance for practical implementation from the beginning onwards.

One particular challenge for the automotive industrial sector, but also for machine construction in general, is the early product definition, often also described as "early stage of product engineering". However, the "early stage of product engineering" is unfortunately less than clearly defined and is in many areas of scientific theses not well-elaborated. Thus, in the automotive industry, the development of a first representation of a vehicle concept can be regarded as early stage of an engineering project. This includes a complete product engineering process including technical solutions as represented by first prototypes. The understanding often put forward in science that this stage is named "early stage" in terms of being functionally orientated, aiming at most for conceptual solutions of product engineering, cannot be agreed on in practical application. The early stage can only be defined in relation to the respective type of product looked at.

The early phase is characterised by the search for a product as well as a by a high degree of uncertainties in boundary conditions and assumptions in the system of objectives. For the automotive engineering sector it is of great importance to already have methods and ways of proceeding in these vehicle definition stages and properly understood early stages in order to be able to reconcile and define possible systems of objectives for future vehicles, which suitably cover future needs.

This is the challenge addressed by the research work of Ms Dr.-Ing. Sabine Muschik with the objective, to methodologically investigate the early stages of product engineering in the engineering process of an automotive manufacturer. Based on this knowledge she has elaborated new concepts and approaches for the engineering process to define the so called “initial system of objectives” in the context of the iPeM – the product engineering process model – which is the central approach in the design research of my group at the IPEK – Institute of Product Engineering Karlsruhe as part of the Karlsruhe Institute of Technology (KIT).

May, 2011 Albert Albers

- To my parents -

Besides what we have actually achieved,
in the end it all comes down
to whether we have gone our own individual way.
(unknown)

abstract

Past decades were characterised by an increase of product complexity due to enhanced technologic feasibilities and a change in attitude of society and demands of customers regarding new products. Especially in the highly competitive automotive industry it is crucial for companies to differentiate themselves from competitors and to consider the multiple, partly contradicting constraints to a future product. To conduct a future product´s development in a target-oriented fashion, valid and consistent product objectives need to be defined in early development stages.

However, early development stages are characterised by high uncertainty regarding the future product and its environment, are only little researched and the possibilities to plan and control them are limited. Thus, this research work pursues the aim to investigate the generation of technical product objectives, especially regarding the aspect of alignment to relevant future constraints. Factors, influencing the generation of objectives were identified and their effects on the quality of objectives were examined. On this basis an approach was developed to enable a reduction of uncertainty by actively influencing those factors and making the respective process accessible to operative planning and control by extending the integrated product engineering model (iPeM). The utility of this approach for industry and its verification is being ensured by an intensive study in the automotive industry.

Due to the complexity of the underlying issue several research areas, amongst which are research on early stages, uncertainty and decision making as well as specific and holistic modelling approaches, are analysed. Insights are specified by an empirical study, which had been conducted in cooperation with the car manufacturer Dr.-Ing. h.c. F. Porsche. Results conclude that issues often emerge during the generation of objectives, because objectives, constraints and their relationships are not understood as a system and respective activities not as a coherent process. Thus, a target-oriented handling of influencing factors, such as methods used or the contributing individuals and an active planning and control of the process is nearly impossible. By defining and using a unified, enhanced comprehension of systems of objectives, the influence of the identified factors on the development of uncertainty in the system of objectives is investigated. A strategy derived on this basis recommends the active influencing of identified factors through the explicit use of such objectives, constraints and related activities to enable the use of operative planning and management approaches in the generation of objectives. For this purpose, a systemic approach to model the process of the generation of objectives is presented, which is able to be adapted situation specifically as part of the modelling framework iPeM. The approach of this thesis is verified by application to the previously studied process environment at the Porsche AG and used in several specific development projects.

Kurzfassung

Die letzten Jahrzehnte waren geprägt von einer, durch die Zunahme verfügbarer Technologien, erhöhten Produktkomplexität und Veränderung der gesellschaftlichen Einstellung und Kundenwünschen gegenüber neuen Produkten. Besonders in der wettbewerbsintensiven Automobilindustrie ist es für Unternehmen entscheidend, sich gegenüber der Konkurrenz zu differenzieren und die vielfältigen, sich teilweise widersprechenden Randbedingungen für ein zukünftiges Produkt zu berücksichtigen. Um dessen Entwicklung zielgerichtet durchführen zu können, müssen dafür bereits in frühen Entwicklungsphasen valide und konsistente Produktziele definiert werden. Allerdings sind frühe Entwicklungsphasen geprägt durch hohe Unsicherheit bezüglich des zukünftigen Produkts und dessen Umfeld, wenig erforscht und nur beschränkt plan- bzw. steuerbar. Die vorliegende Arbeit verfolgt daher die Zielsetzung, die Entstehung von technischen Produktzielen speziell unter dem Aspekt der Ausrichtung an zukünftigen Randbedingungen zu untersuchen. Faktoren, die die Zielentstehung beeinträchtigen werden identifiziert und Auswirkungen auf die Güte von Zielen untersucht. Auf dieser Basis wird ein Ansatz entwickelt, der Reduktion von Unsicherheit durch aktive Beeinflussung der Faktoren und Operationalisierung des Prozesses auf Basis einer Erweiterung des integrierten Produktentstehungsmodells (iPeM) ermöglicht. Die Eignung des Ansatzes für Industrie und dessen Verifikation wird durch eine umfassende Studie in der Automobilindustrie sichergestellt.

Aufgrund der Vielschichtigkeit der Problemstellung werden Forschungsfelder u.a. zu frühen Phasen, Unsicherheit, Entscheidungsfindung und spezifische und holistische Modellierungsansätze analysiert. Im Rahmen einer Studie in Kooperation mit dem Sportwagenbauer Dr.-Ing. h.c. F. Porsche werden diese Erkenntnisse spezifiziert. Es wird abgeleitet, dass Probleme bei der Zielentstehung oft daraus resultieren, dass Ziele, Randbedingungen und deren Beziehung nicht als System, bzw. zugehörige Aktivitäten nicht als zusammenhängender Prozess verstanden werden. Daher ist ein gezielter Umgang mit Einflussfaktoren wie z.B. genutzte Methoden oder beteiligten Mitarbeitern selbst und operationale Planung und Steuerung des Prozesses nur eingeschränkt möglich. Auf Grundlage eines vereinheitlichten, erweiterten Zielsystemverständnisses wird der Einfluss der Faktoren auf die Entwicklung von Unsicherheit im Zielsystem untersucht. Die darauf basierende Strategie empfiehlt die aktive Beeinflussung der identifizierten Faktoren und Zugänglichmachung des Prozesses der Zielsystementwicklung für operative Planung und Steuerung durch Explikation betrachteter Ziele, Randbedingungen und zugehöriger Aktivitäten. Hierzu wird eine systemische Modellierung des Prozesses der Zielsystementstehung vorgestellt, die als Teil des Modellierungsrahmenwerks iPeM situationsspezifisch adaptiert werden kann. Der vorgestellte Ansatz wird durch Anwendung auf den vorab untersuchten Prozess und in mehreren Entwicklungsprojekten der Porsche AG verifiziert.

Acknowledgements

This thesis has been developed as part of my assignment to a three-year research work carried out in collaboration of the IPEK – Institute of Product Engineering (Karlsruhe Institute of Technology (KIT)) with the Dr.-Ing. h.c. F. Porsche AG.

I was especially happy to have Prof. Dr.-Ing. Dr. h.c. Albert Albers as my main supervisor to this research work due to my close ties to the IPEK, which emerged during my first job a student assistant early in my course of studies and accompanied my whole academic life including diploma thesis. Besides outstanding professional talks on the research subject, I owe my gratitude to his trust in my abilities and his motivation to approach this complex issue, which currently ranks among the key research topics of the IPEK. In particular, I would like to thank for the possibility to make a contribution to intensify the research collaboration of the IPEK with the Engineering Design Centre (EDC) in Cambridge, UK by having Prof. P. John Clarkson as a co-supervisor.

On that account I would like to express my great appreciation to Prof. P. John Clarkson for accepting the co-supervision, his interest in my research and valuable advice. Likewise, I would like to thank Prof. Cheng for chairing the final examination.

The possibility to develop and implement my research in an industrial environment enriched the content of this thesis, but also enlarged my professional and personal experience. For giving me this opportunity and constant support during the project I would like to thank Dipl.-Ing. Armin Müller, Dipl.-Ing. Michael Dimitrov and Dipl.-Ing Oliver Grandel from the Dr.-Ing.-h.c. F. Porsche AG and all contributing colleagues.

I have received the probably most sustainable and formative impulses for my research from very interesting discussions with Claudia Eckert, PhD, Senior Lecturer at the Open University, UK. I would like express my respect for her profound thoughts on my research and repeated reassurance to realise my ideas.

Additionally, I would like to thank Dipl.-Ing. Björn Ebel, Dipl.-Ing. Andreas Braun and Dipl.-Ing. Quentin Lohmeyer for the constructive collaboration, facilitating exchange between Weissach and Karlsruhe a lot. Further thanks to all my supervised students, especially Nikola Bursac for supporting me in the last part of my thesis elaboration.

To have the opportunity and to pursue such a challenge is above all to be granted to a blessing with good health, a certain portion of luck and the continuous and encompassing backing of my family and my partner. With their unquestioning trust in me, they raised my own belief in myself to “move mountains” if needed. Thus, they receive all my deepest sincere thanks. I hope I will have the opportunity to pay back!

Karlsruhe, May 2011,

Sabine Muschik

Contents

1 Introduction

In November 1959, the Ford Motor Company retracted the Ford Edsel from the American market. This was the final conclusion to a product failure, which has become synonymous for a disregard of market realities, offering a wrong product for an inadequate market at the wrong time.

The risky decision to develop the Ford Edsel as a new product line in a new division, which meant a change in corporate strategy and decentralisation of Ford´s organisational structure, can be led back to Ford`s attempts to overtake the big competitor General Motors. The aim was to gain shares of the mid-size car market segment by offering a car with distinguishing features, even though development costs and potential success were uncertain. After conducting market analyses and extensive advertisement campaigns, the car was launched in 1957. Even though equipped with innovative technologies (e.g. self-adjusting brakes) and overloaded with design and accessory features (e.g. front grille), customers rejected the uneconomic car and turned to smaller, less expensive and more fuel efficient cars.[1]

1.1 Problem Specification

Although Ford had invested around 250 billion US-Dollars into developing the Ford Edsel and had conducted several market studies to anticipate the customers taste, the product still did not suit constraints of the market at product launch. Also the recent past offers various examples of products, which did not succeed as expected, such as the Audi A2, being technologically superb with the best aerodynamic values ever achieved by a series car or the VW Phaeton, equipped with high class features, both rejected by targeted customers.[2] What had caused these products to fail?

1.1.1 Multitude of Constraints

The launch of the Ford Edsel in 1957 came just in time with an economic recession in the US. This unanticipated constraint had several side effects (Figure 1-1). The Ford Edsel had been placed in the mid-size car segment, for which planners had estimated a potential to sell 210,000 cars in the first year. Due to the crisis, customers with less money to spend turned to the emerging market of small cars (e.g. VW Beetle). The mid-size car segment declined (recovered not until the mid 60´s) and car dealers gave huge discounts on car models of competitors still in stock.

[1] cp. to Deutsch 1976, pp. 41, Dicke 2010, pp. 488
[2] cp. to Dicke 2010, pp. 490, Flohr 2008, n-tv 2010

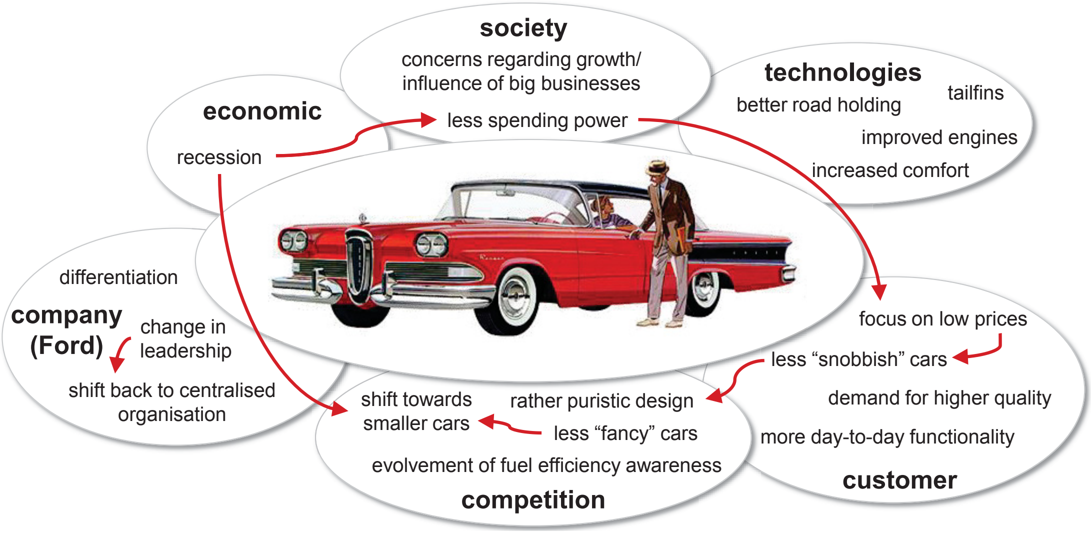

Figure 1-1: The Ford Edsel and its environment at market launch[3]

The slightly overpriced Ford Edsel remained no option for the customer and only 110,000 cars were sold in the end. Results of market analyses had suggested the car should represent style and power as prestigious object for successful professionals or families. However, customers had come to reject excessive car designs of the beginning 50´s. The public perceived the car as snobbish and overburdened. Moreover, due to further internal strategy shifts, the car was produced on the same assembly lines as Ford Lincoln and Mercury, leading to problems in quality and spare parts. These shifts happened due to a leadership change at Ford, causing the project to lose internal backing, finally resulting in the retraction of the car from the market.[4]

Today, the automobile industry is on the verge of a technology shift. The rise of CO_2 due to fuel emissions[5] and the increasing use of natural resources[6] have led to a persistent public discussion. Results are amongst others multiple legal regulations[7], limiting harmful pollution in fuel emissions and a grown awareness of customers concerning fuel efficiency of cars. This development forces car makers to present new solutions concerning propulsion technologies. But companies are cautious on a commitment to one technological alternative, since predictions are contradictive regarding the leading future propulsion technology (e.g. electronic propulsion, fuel cell, combustion engine)[8]. The anticipation and decision for the *right* future will have a huge influence on the success of each company´s products.

[3] own illustration, car graphic: www.flimjo.com (10/12/18)
[4] cp. to Dicke 2010, Deutsch 1976, pp. 40/43
[5] 1990-2007: CO_2-emissions +38 % (p.44, International Energy Agency 2009a)
[6] 2007-2030: primary energy supply by fuel (oil) +25,5% (p.8/48, International Energy Agency 2009b)
[7] e.g. CO_2-emission (new passenger vehicles) limited to 130 g/km by 2015, European Parliament 2009
[8] e.g. forecast on share of propulsion technologies in vehicle sales 2025, Oliver Wyman 2009

These examples outline just an extract of the dynamic environment a new vehicle concept needs to face up to today. Constraints are growing in number, diversity and even if considered at project start they may be outdated at product launch.

1.1.2 The Translation Issue

The challenge is to consider such constraints already in the development of a new product. Some seem to be unforeseeable, such as in the case of the Ford Edsel, the economic crisis or the sudden heart attack of the project leader, causing a change in leadership and thus in the product´s strategy.[9] Ford was way ahead of time to be aware of customers as a critical factor for product success. Unfortunately, a poor choice of methods in market analyses led to a misjudgement of the future customer. Studies focused on personal identification with a car, not on prices or operation cost. They projected past trends into the future without considering dynamic changes, causing the conception of the car to be placed and designed for a wrong segment. Since the rising awareness for fuel efficiency was not predicted, the Ford Edsel´s engine parameters were incorrectly defined to be powerful instead of efficient.

This example outlines the difficulties in handling constraints of the environment but also of the own company in engineering projects. They may be unforeseen, not detected, misjudged and relationships between them might remain undetected. Their final validity seems to be strongly dependent on means used for their anticipation. The ill-defined dimensions of the Ford Edsel engine are a show case for the need that important parameters of a product have to be consistent to relevant constraints. In product engineering future product parameters are anticipated by technical objectives to enable target-oriented development. Thus, it can only be ensured that a future product parameter satisfies its constraints, if these are incorporated already in the definition of the respective technical objective, even before actual development activities start. To consider the relevant interrelated, often qualitative constraints in the generation of a quantitative technical objective, these need to be converted to be technically measurable. But in such early engineering stages not many details about the future product and its parameters are in fact known. Relationships between parameters, in later stages handable by calculation or CAD-models, remain fuzzy. This impedes a consistent identification and definition of objectives, as the example of the VW Phaeton showed. Responsible engineers certainly defined an objective for fuel consumption. But this objective probably did not sufficiently account for additional weight of various technologies incorporated in the product concept and their effect on fuel consumption leading to inconsistencies in the product´s objectives.

[9] cp. to Dicke 2010, p. 493

These interdependencies caused an increased fuel consumption of the finished car. In addition to underrating the rising importance of low fuel consumption for customers in high class cars, this was one reason for an impaired success of the car.[10]

1.1.3 Problem Delimitation

The past examples outlined cases in automotive history, known especially for their deficiencies in the car concept. Opposed to these are multiple market successes, allowing the assumption that respective companies must have done something right in aligning the concept to potential market constraints. If this had happened by chance or in fact controlled, cannot be judged without knowing about a company´s internal product engineering process. On top, also successful companies face the rapid growth of constraints and a need for product differentiation. Success in leading a car segment by stand-alone products is not possible anymore. Even the hitherto untouched sports car segment faces claims for its role in environmental pollution.

This shows that there is a need to identify those factors, which influence the generation of valid technical objectives and their alignment to the multiple, diverse, dynamic and interrelated future constraints. A delimitation of potential obstacles in this process is necessary to be able to outline ways, how to minimise the risk of a diminished market success caused by products, which are not properly suiting future demands (Figure 1-2). This challenge is addressed as a key issue by this thesis:

Problem Statement

The generation of valid technical objectives aligned to relevant constraints from environment, market and company, as basis to defining an engineering project to develop a successful product, has not been satisfactorily resolved.

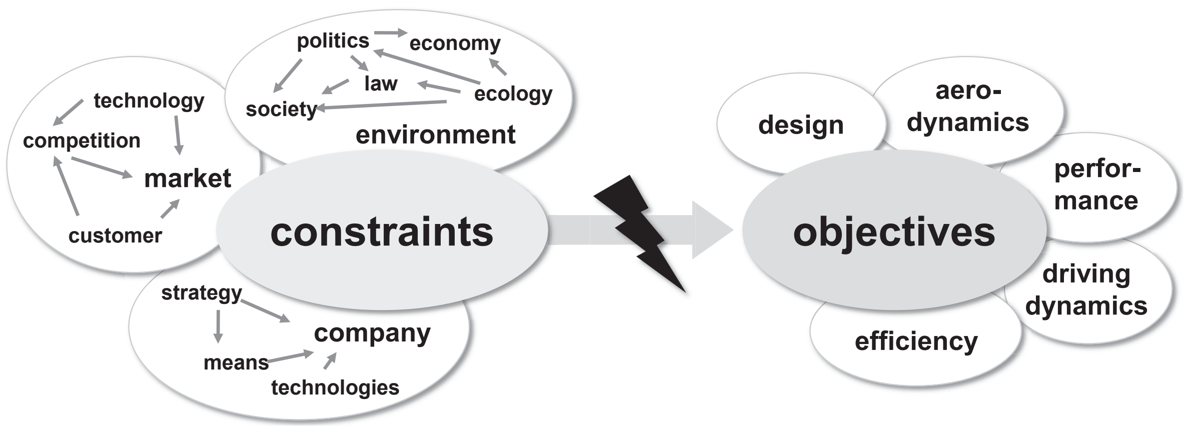

Figure 1-2: Fundamental conflict

[10] cp. to n-tv 2010

Two key questions need to be answered to be able to solve this issue:

- Which problems occur during the generation of technical objectives and their alignment to relevant constraints?
- How can such problems be overcome, i.e. valid technical objectives be generated whilst maintaining alignment to relevant constraints?

1.2 Research Motivation

1.2.1 Research Perspective

Identifying solution approaches from research regarding the detected problem it becomes obvious that several distinct research fields touch parts of the problem. Research on constraints focuses mainly on classifying constraints and proposing distinct methods and tools on how to elicit especially exogenous constraints (e.g. trend or competitive analysis, summarised as *environmental analyses* in Figure 1-3). Research on objectives is addressed with emphasis on its significance to decision making and problem solving. Further research investigates early stages as a project environment in which objectives are generated. These studies mainly originate from innovation management research and focus on peculiarities and related difficulties for engineering projects.[11] Several modelling approaches include the notion of constraints as modelling parameters (e.g. HALES and GOOCH), but there are no modelling constraints as input parameters to the definition of an objective. Most approaches on handling objectives (e.g. requirements engineering) spend little time on depicting the *generation* of objectives and do not provide solutions on how the various dynamic constraints may be integrated in their formulation. The systemic perspective in research includes the most extensive approach to model objectives. With the integrated product engineering model (iPeM), ALBERS has transferred this systemic understanding into a broader product engineering context.[12] IPeM is therefore considered adequate as a basic modelling framework for the assessment of the key problem of this research work. Even though existing literature provides a basis to understand issues in early stages, it does not offer a holistic perspective on the problem context. The process of generating objectives as a part of their overall development has only been little reviewed especially regarding the question how constraints are in fact considered in their formulation and which problems impede this process. Thus, also actual handling and improvement of such a process cannot be depicted with given approaches. This leads to the following research demand:

[11] e.g. Koen et al. 2001, Khurana & Rosenthal 1997
[12] cp. to Albers 2010

Research Demand

Existing literature does not provide a holistic perspective on the generation of objectives and their alignment to essential product constraints. Thus, an assessment of existing processes that improve the consideration of constraints in objectives with given approaches is not possible.

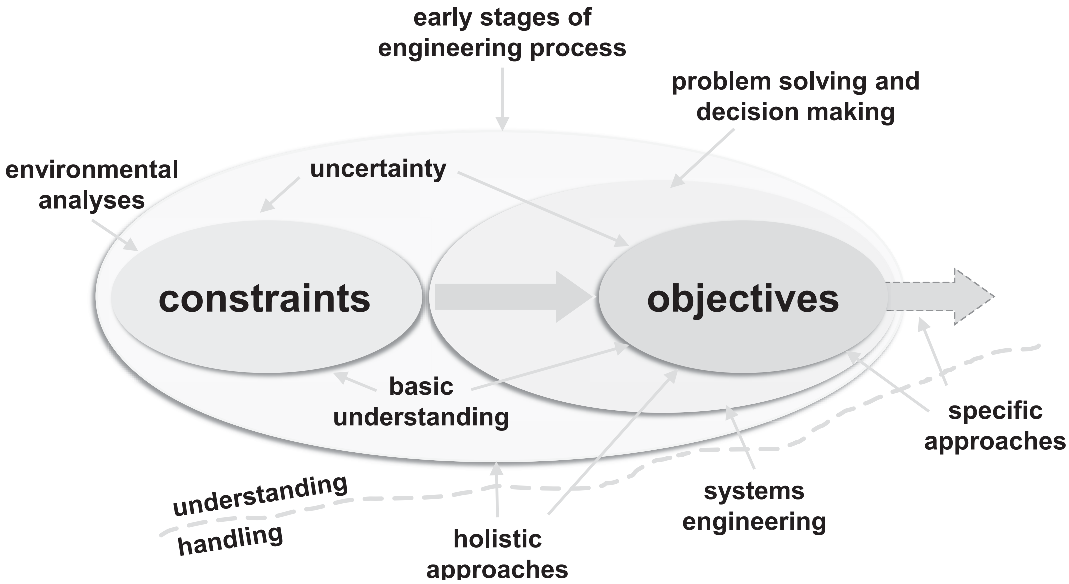

Figure 1-3: Research fields

1.2.2 Industrial Perspective

Technical objectives are essential as criteria for product decisions. Since companies strive to get more efficient regarding time and cost in product engineering, they aim on defining objectives for the most essential product parameters as early as possible in the development process to avoid expensive rework due to adaptations in later stages. Early engineering stages offer the biggest potential to define factors of particular importance to the success of the product. However, today the high uncertainty in early product engineering stages still imposes a problem to systematically generate valid objectives under consideration of relevant constraints. Additionally, there is insufficient support for the conduction of respective processes.[13]

Industrial Demand

The derivation of valid and consistent objectives based on relevant constraints early in the engineering process is crucial for the success of an engineering project. However, there is little support for such processes.

[13] cp. to Albers et al. 2010g, pp. 8

1.3 Research Approach

1.3.1 Research Hypotheses and Questions

This research is based on four research hypotheses. These are derived from the current state of literature as presented in Chapter 3. They constitute the basis for the formulation of respective research questions, which shall guide the verification of the research hypotheses throughout the thesis. The first two hypotheses address the first part of the problem specification in section 1.1.3. The first hypothesis deals with the actual embedding of the generation of objectives in product engineering processes:

> **Research Hypothesis 1**
>
> Technical objectives are generated by activities,[14] which are carried out mainly implicitly by different involved individuals with little central regulation. This impedes an active and efficient support of this process.
>
> **Research Question 1**
>
> How are technical product objectives generated, how are constraints from the market, product environment and company considered and which factors influence this process?

The second research hypothesis focuses on the reasons, why a valid generation of objectives and consideration of constraints does not always succeed:

> **Research Hypothesis 2**
>
> The development of objectives and the way and extent to which constraints are considered depends on various influencing factors and their interdependencies.
>
> **Research Question 2**
>
> Which factors influence the development of objectives and in what way?

The second two hypotheses pave the way for an approach to solve the second part of the problem specification as stated in section 1.1.3. Therefore, the third research hypothesis focuses on how the development of objectives can be improved:

> **Research Hypothesis 3**
>
> The development of improved objectives can be achieved by actively manipulating the influencing factors.

[14] An *activity* is understood as composed of an operation and respective resources. Arranged in a sequence, activities constitute the smallest elements of processes (cp. to Meboldt 2008, p. 159).

Research Question 3

Which of the factors can be influenced and in what way?

The fourth hypothesis relates to the role of the modelling framework, which is used as a basis for implementing the improvement approach.

Research Hypothesis 4

The development of objectives can be made explicit by using the systemic modelling framework of iPeM, making the process accessible to active improvement and management.

Research Question 4

How can the development of systems of objectives be made explicit and thus manageable and improvable for operative use within the modelling framework of iPeM?

1.3.2 Research Scope and Contribution

This research is grounded on insights from extensive studies in the car industry as well as a systematic analysis of theoretical approaches. In building the thesis both inductively and deductively, an applicability of the results shall be ensured.

The results of this research aim at two main contributions for the stakeholders in research and practice. The first contribution is to provide a detailed understanding of how objectives are in fact generated and which factors may impede an optimal integration of constraints and thus generation of valid objectives. Secondly, an approach is provided, which shall enable the stakeholders to actively regulate this process to improve the generation of objectives in early stages.

This research work proposes an integrated modelling framework and thus does not focus on developing specific new methods, unlike various other approaches from related research, e.g. methods to elicit customer requirements. Furthermore, this research does not address the transformation of objectives into the actual product.

1.4 Thesis Outline

- ***Introduction:*** The research topic is motivated based on current issues and its relevance for research and practice. The research questions guiding the course of the thesis are outlined and the basic hypotheses are stated. The content of the thesis is delimited and contributions to stakeholders are stated.
- ***Methodology:*** The methodology, which has been used to elaborate the contents of this thesis, is outlined to reveal the argumentative structure and scientific procedure on which the findings of this research work are grounded.

- ***State of the Art:*** Relevant research fields (section 1.2.1) are reviewed regarding findings on the research issue. It is found that the distinct fields highlight aspects, but do not take a holistic perspective on the difficulties during the generation of objectives and how such a process can be actively managed.
- ***Aim of Research:*** The problem statement is specified according to the identified gaps in current literature. On this basis, the guiding research hypotheses and questions as well as the research objectives for the approach of this thesis and for the elaboration of the approach are derived.
- ***The Empirical Case:*** This chapter outlines the extensive empirical study, which was carried out at the German car manufacturer Dr.-Ing. h. c. F. Porsche AG to investigate the identified problem in practice. It describes the environment in which constraints are being elicited and objectives are generated. It shows that respective activities are carried out mainly implicitly by different involved individuals with little central regulation. Several influencing factors are found to have an effect on the activities and finally on the formulation of objectives.
- ***The Development of Systems of Objectives:*** Based on the finding that the consideration of constraints is essential for validating objectives, this chapter establishes a theory to understand and describe what happens during the development of objectives. After providing an extended definition of a system of objectives including constraints, it is argued that the development of systems of objectives can be described as a reduction of uncertainty by completing and concretising the content of the system. This section concludes with the basic strategy of the approach to improve the generation of objectives and consideration of constraints by proposing an active manipulation of influenceable factors alongside flexible planning and execution of activities.
- ***Modelling the Development of Systems of Objectives:*** To be able to use this strategy in operative work, this chapter presents means to make elements contributing to the generation of objectives explicit and depict their inter-dependencies. The systemic modelling framework of iPeM is extended to provide an explicit and flexible modelling representation of the interface between objectives and respective activities.
- ***Application to the Empirical Case:*** The developed approach is applied to the empirical case as introduced in Chapter 5. The modelling approach is tailored to the specific company conditions to support planning and managing the process of integrating constraints into the generation of objectives.
- ***Conclusions and Further Work:*** The results of the thesis are summarised and the elaborated response to the initial research questions is evaluated. The contributions are discussed and further work is outlined.

2 Methodology

This section gives an overview of the applied methodological procedure in this thesis. As a basis for the methodological structure, the spiral model of design research of ECKERT et al.[15] has been used. This research methodology provides a framework, applicable to different forms of research, not only to those improving design, but also to those increasing the understanding of design. This differentiates the methodology to other design research approaches, allowing research to begin with any of eight research objectives (Figure 2-1, entry points marked with arrows), as long as it is linked to a bigger research context. One reason why this methodology was chosen was that it integrates a practical perspective on research. This is especially important for results of this research, since it is strongly related to solving an industrial need.[16]

Figure 2-1 shows the chapters of this thesis aligned to the spiral model. Empirical research conducted in Chapter 5 specifies findings from literature research by studying the specified problem in practice. This investigation aims to ensure the practical relevance of the research scope and defines requirements for applicability of theory and procedures to be developed.

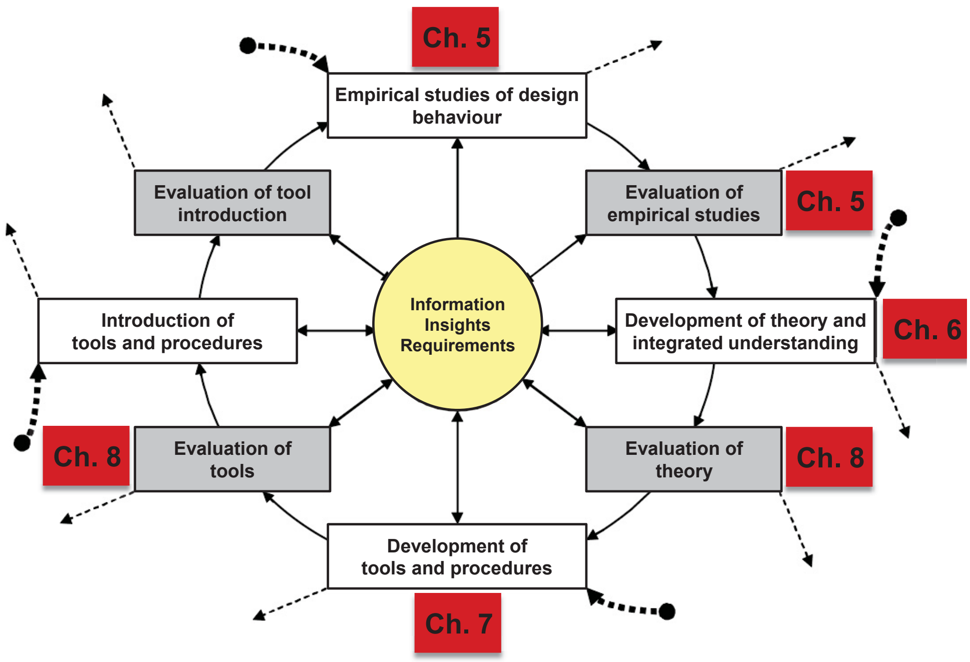

Figure 2-1: Structure of thesis in spiral model of design research[17]

[15] cp. Eckert et al. 2003
[16] for further information on the methodology, refer to Eckert et al. 2003, Eckert et al. 2004
[17] based on Eckert et al. 2004, p. 2

The findings are evaluated regarding their generalisability by comparing them to findings from other empirical studies. Chapter 6 uses insights and examples from Chapter 5 to develop a thorough understanding of objectives and constraints and a theory on how they develop throughout early stages in product engineering. This chapter is the basis for developing a modelling framework in Chapter 7. Both the theoretic conclusions and modelling framework are evaluated in Chapter 8. This evaluation is done by applying the approach to the industrial environment of the empirical study of Chapter 5. The approach was deductively adapted to the specific conditions of the process environment and could be verified during several project conductions. Insights from project conductions could be inductively transferred back to further develop the procedure and the model. The success criterion for this approach was the value perceived by applying the approach in industry.[18]

2.1 Empirical Research

The empirical evidence used in this thesis was collected in a research collaboration in which the author spent three years working at the Dr.-Ing. h. c. F. Porsche AG, while in parallel conducting research at the IPEK – Institute of Product Engineering, a research institution of the Karlsruhe Institute of Technology (KIT). During this project, the author made two explicit case studies and continuously participated in operational engineering activities in the advanced development department. Several research methods were applied to collect evidence about industrial issues related to the basic research questions. According to the classification of YIN, these were the:[19]

- conduction of formal and informal interviews
- collection and analysis of *documents*
- participant *observation*

These methods were continuously applied during the project, whereas an implementation of specific methods depended on the state of the project, i.e. the level and degree of concretisation of information and knowledge already collected.

Findings from initial *observations* of the author in daily work determined further research directions based on perceived current issues. The author contributed in projects by elaborating specific tasks and took part in regular and unscheduled meetings and workshops. Further observation opportunities emerged by the author´s supervision of student theses and internships in the department as well as leading an own project on improving the departments information and knowledge management.

[18] cp. to Eckert et al. 2004, p. 6
[19] cp. to Yin 2009

Another substantial part of evidence played *internal documents* analysed during the research project. In the beginning, the analysis focused on a basic understanding of the company´s product engineering process environment, especially concerning its early stage. The aim was to find out about the degree of standardisation regarding processes, methods and tools to be able to compare it later to insights of actual practice. On the basis of grown knowledge, also granted to the observations made, the analysis of documents focused on specific elaborations, such as reports or presentations, likely to provide further information on the research questions raised.

These basic sources of evidence were complemented by two focused case studies, using formal and informal interviews to answer specific questions, which emerged throughout the project and were assumed to clarify the research issues. The first study, conducted during the first stage of the research project aimed on concretising the picture on activities performed before a first product specification to generate technical objectives and consider constraints. The key data of this study is listed in Table 2-1. Interviews were conducted semi-structured. They based on initially defined questions, identified on the basis of observations and analysed documents. Selection and formulation of questions was accompanied by a review and discussion with the responsible team leader. Being semi-structured, the questions framed the interviews, allowing a comparison of results but still left room for further questions, when necessary in the course of an interview. The team leader joined the interviews, enabling the author to precisely document the talk as well as for the experienced team leader to identify and ask for further information. The interviews lasted about an hour and were subsequently fully documented and analysed by the author.

A second empirical study was conducted in the second half of the research project. The need for it was identified in intermediate results from investigations and the substantiated research hypotheses due to concurrent literature review. Assumptions that the development and quality[20] of objectives was also influenced by high uncertainty, subjectivity of decision making as well as imperfection of information and knowledge used, led to the formulation of more detailed questions.[21]

Table 2-1: Main information on case studies

	# interviews	**# departments**	**# of different hierarchical levels**
Case Study 1	21	21 (3 diff. resorts)	2 (engineers/manager)
Case Study 2	17	7 (1 resort)	4 (engineers / three managerial levels)

[20] The quality of objectives is subsequently understood as its *validity*, *comparability* and *consistency* in the system of objectives (derivation, explanation and ways of measurement in Chapter 5 and 6).

[21] see Section 3.1 and appendix, Figure A-1

They formed the basis for further semi-structured interviews. These lasted about an hour and were subsequently fully documented. The evaluation of findings was done by the author and another research associate from the IPEK independently from each other. Individual findings were discussed to identify influencing factors on the development of objectives during decision making processes in early engineering stages. The studies were accompanied by various informal interviews with colleagues and managers in the department and integrated in the elaborations of the overall findings. Both studies were evaluated together with respective documentary material and observations taking the initially defined research questions as a guide.

To validate the research approach developed in this thesis and to fulfil the practical research objective, the approach was implemented in the environment of the empirical study to prove its effectiveness and improve existing issues.[22]

2.2 Building Theory

Theory in this thesis is derived deductively from the state of the art and own insights and inductively from the empirical case, as studied in Chapter 5. Thus, the theoretical approach was developed iteratively by generalising from insights of the empirical case and other case studies from literature. The explanation of theory in Chapter 6 and a part of the verification of the approach in Chapter 8 is thus illustrated with extracts from a consistent example from one project studied during the research collaboration at the Dr.-Ing. h.c. F. Porsche AG (see exemplary extract in Figure 2-2). This project is a representative example of many projects analysed in the empirical study. It is a reconstruction of a specific conduction of an environment analysis and prognosis carried out in 2007. This specific example was chosen, since the environment predicted then can now be evaluated and verified against reality. [23]The author used documentary material, observations and interviews with individuals, who participated in the project to develop a visualisation of knowledge and information used to derive results. The visualisation tries to capture explicit and implicit knowledge, thus serves to explain the abstract system of objectives developed in that project. To reduce complexity, it highlights information and knowledge used for predicting one specific competitor car. It serves to illustrate theoretic reflections and is by no means meant to represent a "complete" system of objectives.[24]

[22] The results are described in Chapter 8.

[23] Internal project data has been anonymised for confidentiality reasons, whenever necessary. Documents from the company or own elaborations from the research collaboration presented in this thesis have been translated into English (company language is German).

[24] It is later argued that a system of objectives can never be objectively complete, see section 0.

To verify the developed approach in Chapter 8, the industrial environment as decribed in the empirical case (Chapter 5) is picked up again. Since theoretic insights could be iteratively verified during the research collaboration, this chapter describes the theoretical approach as implemented in the empirical environment. It outlines the derivation of a reference process and according procedures. The subsequently presented verification of the applied approach in a specific project draws both on insights from current projects, but also on the previously described example project. Although the approach had been tested on several new projects, this description uses again data of the project from 2007 to be able to compare results of before and after the implementation and to verify predictions on the basis of the new theoretical approach. During verification of the approach in this research, the reference model was iteratively and inductively improved based on the insights from the application.

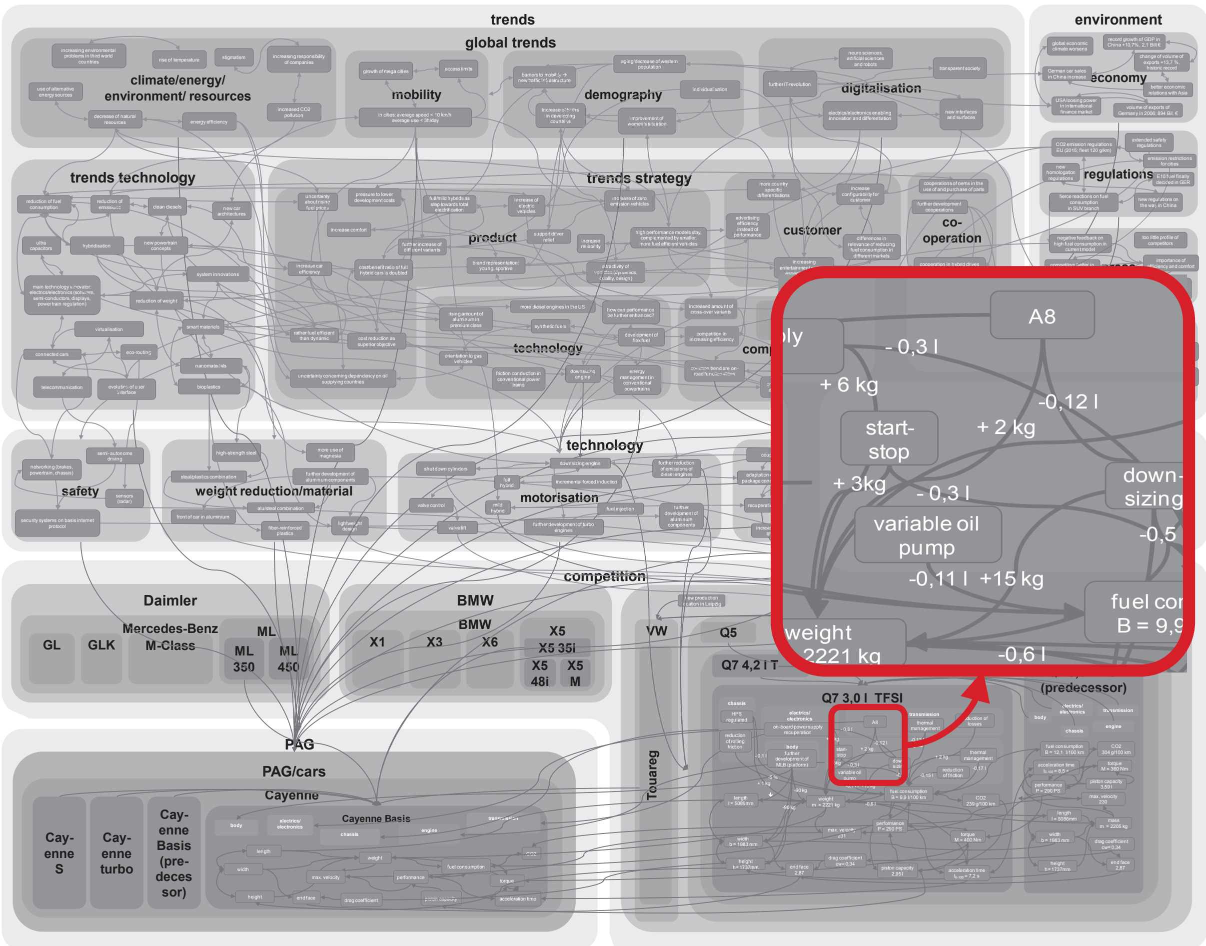

Figure 2-2: Extract of a visualisation of a system of objectives for a specific project[25]

[25] Figure 2-2 only serves to give an idea about the complexity of a system of objectives. Due to the multitude of elements and dependencies, readability is obviously limited. Thus, whenever it is referred to the contents of Figure 2-2 in this thesis, the specific extracts are highlighted.

3 State of the Art

The example of the failure of the Ford Edsel on the American automotive market outlined the challenge which companies face to align their products to constraints which are of particular importance to future product success. This chapter reviews approaches from research relevant in addressing this challenge.

The primary section approaches an understanding of constraints, objectives and their correlation in a product engineering context. It aims to carve out the present research opinion on difficulties, which impede an adequate consideration of constraints in objectives for the subsequent development process. The second section examines research approaches, which propose solutions to a handling of this process. Thus, it strives for filtering out a suitable basis and requirements for an approach to support process planning and management. Insights from this chapter reveal the lack in a holistic perspective of current research on the initially formulated problem statement.

3.1 Constraints and Objectives in Early Product Engineering

This section investigates how literature addresses constraints, objectives and their correlation in the context of early product engineering. It elaborates answers to the following questions:

- *Understanding of objectives and constraints*: How do different research approaches understand objectives, constraints and their coherence?
- *Early stages*: What is known about the relevant project environment and its difficulties for eliciting constraints and generating objectives?
- *Constraints to future products*: Which exogenous and endogenous constraints have been found relevant to be considered in future products?
- *Role of uncertainty*: How is the presence of uncertainty and its mitigation discussed in the context of future-oriented constraints and objectives?
- *Problem solving and decision making*: How is the role of objectives for problem solving processes understood, which requirements are proposed for formulating objectives and which factors impede the derivation of this formulation?

This section concludes that research areas address the problem from a constraint-focused or objective-focused perspective or discuss general issues for early engineering stages (Figure 1-3). A holistic comprehension of the generation of objectives, the role of constraints in this process and associated problems has not been built yet.

3.1.1 Understanding of Objectives and Constraints

This section discusses terms and definitions for objectives and constraints used in different research approaches. It concludes that the various different terms and understandings are one cause why there is no holistic approach to the coherence between objectives and constraints in research and industry.

3.1.1.1 Different Terms and Definitions

There are various terms used in engineering design theory and practice for describing future properties of a product, which are intended to be accomplished or attained during the product engineering process.

An *objective* describes "something, towards which effort is directed"[26]. In contrary to a *goal*, which is to be achieved only by continuous, long-term effort, an *objective* implies something tangible, which is attainable in reasonable time. The term *objective* indicates a strategic position to be achieved and is thus often used in the context of research on strategy.[27] It is also often found in publications on and in practical use in the automotive industry to describe future product properties. The use of the term *goal* can be found, for example, in NEGELE et al..[28]

The term *requirement* distinguishes "something wanted or needed."[29] In engineering, a requirement is understood as a desired, technically evaluable should-be product property. The generation of requirements bases on environmental constraints, focussing on customer and user requirements (especially in software engineering).[30] Requirements engineering rather concentrates on ensuring the transformation of detailed requirements into product functions, than on strategically positioning product properties. The research area affordance-based design is a new direction of research, using so-called *affordances*[31] to derive product functions based on interaction of designer and user.[32] Some approaches refer to *objectives* as future product properties, being independent from a specific solution, from which solution specific *requirements* to the product are derived.[33] Further approaches completely summarise future product properties with *requirements.*[34]

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[26] cp. to Encyclopedia Britannica Online 2010c, query "intention" (10/0810)
[27] cp. to Encyclopedia Britannica Online 2010b, query "objective" (10/08/10)
[28] e.g. Negele et al. 1999, see also Hubka & Eder 1996
[29] cp. to Merriam Webster Online 2010a, query "requirement" (10/12/08)
[30] cp. to Ehrlenspiel 2007, pp. 365, Eiletz 1999, pp. 11
[31] "The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill.", Maier & Fadel 2009, p. 20, citing Gibson 1979
[32] cp. to Maier & Fadel 2009
[33] cp. to Bader 2007, pp. 12, see also Pohl 2008, p. 90
[34] see overview of examples in Ahrens 2000

Other approaches understand objectives as comprising solution specific requirements, derived from solution independent objectives in later development stages. Here, the term *objective* is used synonymous to *requirement*.[35]

Constraints as constraining conditions are discussed by HUBKA and EDER as limitations to certain properties, such as decisions of society, e.g. regulations.[36] Further approaches use the term *value* for describing constraints, especially for relevant stakeholders of a product. Such approaches focus on ensuring a consideration of values in the definition of objectives of the later product.[37]

3.1.1.2 Implications

This section has shown that there are different understandings of how future product properties are describable and on which basis they are derived. The variety of approaches, mainly due to specific research objectives or the respective industrial utilisation, has impeded the evolution of a common understanding of the coherence between constraints and objectives.[38] This thesis will refer to the following definitions:

Definition 3-1: Constraint

The term *constraints* shall be used as a collective term for all demands, including values, relevant to the generation of future product properties, arising from within (endogenous) or without (exogenous) a company.[39]

Definition 3-2: Objective

The term *objective* describes anticipated future product properties, underlining the strategic importance of objectives in product engineering. It is equivalent to the term *requirement,* if used to describe a future product property.[40]

Figure 3-1: Delimitation of constraints and objectives

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[35] cp. to Eiletz 1999, pp. 11

[36] cp. to Hubka & Eder 1988, p. 154, see also Pohl 2008, p. 18, Merriam Webster Online 2010b, query “constraint” (10/12/08)

[37] for example Rebentisch et al. 2005, Hall 1962 (value system design)

[38] This thesis understands constraints and objectives as part of a system of objectives (Chapter 6/7).

[39] *Constraint* is preferred to *boundary conditions* in this thesis due to its meaning, implying that a constraint is a *constraining* condition (Merriam Webster Online 2010b) in respect to an objective.

[40] cp. to Albers 2010 (strategic importance of objectives), Ehrlenspiel 2007 (understanding of requirements as future product property)

3.1.2 Early Stages in Product Engineering

As mentioned in the introduction, the greatest benefit of a reliable definition of a product´s objectives aligned to its relevant constraints can only be achieved as early in the product engineering process as possible, when actual development activities have not even begun. This stage in a product engineering project is often referred to as the *early stage*[41] or *fuzzy front end*[42] in literature. Empirical studies verify its leveraging effect by showing that deviations to objectives in later stages are mainly influenced by activities in early stages.[43] The next sections discuss studies on early stages. It is found that peculiarities of this stage are to be considered as important factor potentially having influence on the consideration of constraints in objectives.

3.1.2.1 Classification in Research

The beginning of product engineering projects has been referred to by different terms in literature. Several approaches believe in its fuzzy character due to activities being unstructured and dynamic. They address such activities as *fuzzy front end*.[44] KOEN et al. propose the expression *front end of innovation*, arguing that *fuzzy* implies included activities to be mysterious causing a lack in accountability in an engineering project.[45]

Several research areas are concerned with the investigation of early stages. A considerable number of empirical studies has been conducted in technology and innovation management, most prominently by KHURANA and ROSENTHAL and KOEN et al..[46] Regarding holistic modelling approaches in product engineering, a depiction of early stages in rather design-focused approaches can be found, for example, in proposed sequences of respective engineering phases, e.g. PAHL and BEITZ.[47] Exogenous and endogenous constraints imposed onto the solution space early in design are not sufficiently addressed by current design-focused approaches.[48]

3.1.2.2 Identification of the Early Stage

Literature does not clearly outline the actual content of early stages, mainly caused by the difficulty to delimit these stages to the subsequent “conventional” product engineering activities.

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[41] e.g. Verworn & Herstatt 2007b,
[42] e.g. Jetter 2005, Khurana & Rosenthal 1997
[43] Verworn & Herstatt 2007b, p. 7
[44] e.g. Khurana & Rosenthal 1997, Jetter 2005
[45] cp. to Koen et al. 2001, p. 46
[46] Khurana & Rosenthal 1997, Koen et al. 2001
[47] e.g. Pahl & Beitz 1995
[48] cp. to Wynn 2007, p. 29, further (project-focused) approaches e.g. Gausemeier et al. 2009, Hales & Gooch 2004, Cooper et al. 2002, pp. 22 (see section 3.2.3.2 for a further evaluation)

Even though stage gate models frequently used in practice suggest a distinct start of these "conventional" product engineering activities,[49] the transition is fluent and conducted activities cannot always be clearly matched to early or later stages.[50] VERWORN and HERSTATT believe the key focus in early stages to be the detection of technical product objectives including all relevant constraints.[51] KHURANA and ROSENTHAL distinguish between two factors (Figure 3-2). *Foundation elements* are project independent and valid for the conduction of all projects of a company. These are product and portfolio strategy and the product engineering organisation with given structure and roles. Such elements need to be considered in each project as endogenous constraints obligatory to the product. *Project specific elements* differ in each project. KHURANA and ROSENTHAL find that opportunities to a project need to be detected by analysing exogenous constraints, such as relevant markets, and demands need to be derived from customer or regulatory constraints as a basis for a first product concept. Ideas for a potential concept have to be generated and selected. The result of early stages should be a clear and aligned first product specification and project plan as an input to the further engineering process.[52] HALES and GOOCH argue that it is especially important in early stages to be aware of the impact of the various constraints on a project to be able to exercise control on them. Constraints impose dynamic influences on the project, which range from strongly positive for the attainment of project objectives to strongly negative.[53]

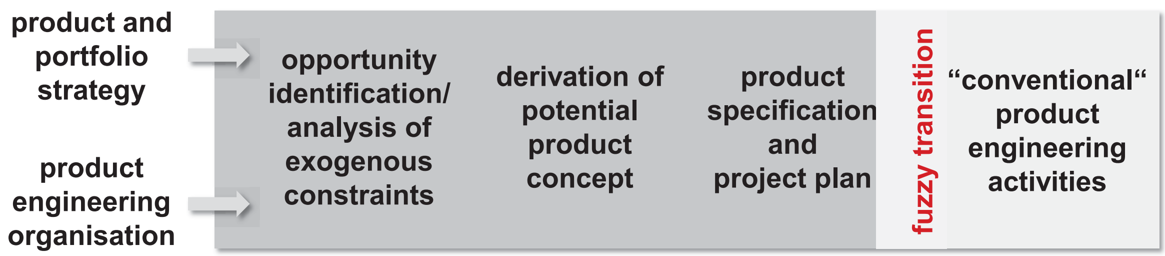

Figure 3-2: Activities in early stages[54]

3.1.2.3 Peculiarities of the Early Stages

As already mentioned, research on early stages has mainly focused on empirical studies, since the dynamic character of this stage aggravates the generalisation of the results.[55] The following lines summarise the findings of main studies.

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[49] official project start, go/no-go decision proposed e.g. by Khurana & Rosenthal 1997, p. 105
[50] cp. to Koen et al. 2001, p. 49, Jetter 2005, pp. 63
[51] cp. Verworn & Herstatt 2007a, p. 113
[52] cp. to Khurana & Rosenthal 1997, p. 105, Koen et al. 2001, p. 47, Pahl & Beitz 1995
[53] cp. to Hales & Gooch 2004, pp. 30, see section 3.1.3 for detailed discussion
[54] cp. to Khurana & Rosenthal 1997, p. 105
[55] see, for example, Jetter 2005

Khurana and Rosenthal analysed the conduction of activities in the early stage in eleven, mostly incremental innovation projects. They found that especially the overall aim of the early stage, the clarification of a first product specification, is difficult to achieve. This is because often the development of a respective description is conducted inconsistently, resulting in unclear and imprecise description statements. A cause can be identified in complex information processes, where knowledge is often only available implicitly and little is documented.[56] Hansen and Andreasen found in an analysis of the structure and content of product specifications in early stages that for the specification of a product idea only few characteristics are necessary to outline its identity and difference. These depend on the context and existing product solutions known on the market. Further requirements only distract from the essential information in this stage. They assume a complete and operational formulation of specifications is not necessary at this point in the project.[57] A further issue is identified in decisions often not founded on given basic strategic considerations of the company, but on the prevailing, project-specific criteria. These criteria are often not aligned to relevant markets and competitor products. Strategic foundation elements can be product platforms. Examples of products build on the basis of a platform aligned to explicit customer, market and technology constraints, showed a successful fulfilment of the defined objectives in the end. [58]

Herstatt et al. compared German and Japanese engineering projects. They found projects aimed to reduce market and technical uncertainty prior to later development stages, which was achieved with varying efficiency. The conduction of the early stage differed in attempts to reduce deviations from early specifications and to enhance efficiency. Attempts could be differentiated by thoroughness and strictness in planning and controlling as well as by support from methods and tools. If little planning and controlling was used, it was ensured that necessary information and points of view were considered as soon as possible in the project and responsibilities were assigned early and rarely changed. No single best way could be extracted from findings of the study. Several empirical studies propose a positive effect of structuring and formalising early stages. In contrast others argue that structure impedes solution freedom and is not suited for early stages.[59]

Considering organisational aspects, Khurana and Rosenthal stated that in most cases cross-functional core teams worked on activities in early stages.

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[56] cp. to Khurana & Rosenthal 1997, pp. 110, Schwankl 2001, Verworn & Herstatt 2007b, p. 13
[57] cp. to Hansen & Andreasen 2007, p. 6
[58] cp. to Khurana & Rosenthal 1997, pp. 108
[59] cp. to Herstatt et al. 2002, p. 22, Verworn & Herstatt 2007a, p. 112, to Khurana & Rosenthal 1997, pp. 104, Koen et al. 2001, pp. 49

Often responsibilities are not clear, participants have different ambitions and discuss highly interdisciplinary issues. A holistic perspective on the future product seems to be helpful rather than a focus on technical details. Reconciliation and communication need to be ensured by senior management. Difficulties occur in verifying consistency of outcomes.[60] Peculiarities of early stages are assumed to depend on the project context, e.g. product novelty, type of organisation or frequency of new projects.[61]

3.1.2.4 Implications

Based on these findings, the subsequent definition was derived for this thesis:[62]

Definition 3-3: Early Stages

The early stage in a specific product engineering project addresses the time range between the trigger for or initiation of an engineering project to the formulation of a first (strategic) product specification.[63]

This implies no exact sequence of engineering activities, but serves to delimit the stage from later project stages in order to address a cumulative appearance of characteristic aspects of early stages (e.g. high uncertainty).

There are two main factors which are important for and characteristic of early stages in engineering projects:[64]

- *degree of uncertainty* concerning constraints and the emerging product
- degree of *formalisation* and *systematisation* of activities

The impact of these factors on the generation of objectives and consideration of objectives has not yet been reviewed. But since early stages provide the environment for generating objectives, they are considered as important factor to be considered as potentially influencing how and to what extent constraints are considered.

3.1.3 Constraints to Product Engineering Projects

The previous review of empirical studies revealed that constraints need to be considered in the engineering process before a product is initially specified. The following paragraphs discuss opinions on why this consideration has become that important and which constraints are in fact considered to be relevant.

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[60] cp. to Khurana & Rosenthal 1997, pp. 108
[61] cp. to Verworn & Herstatt 2007b, p. 13
[62] based on Verworn & Herstatt 2007b, p. 8
[63] A product specification is understood as description of the product to be developed on the basis of its main technical parameters, technologies and product components to be included.
[64] cp. Verworn & Herstatt 2007a, pp. 113, cp. to Khurana & Rosenthal 1997, p. 108

3.1.3.1 Evolution of the Role of Constraints for Product Engineering

One reason that constraints have become even more important is that the role of technology and its impact on environment as well as on society and vice versa has grown due to its great evolution in the last century. Positive effects are higher availability of technology for more parts of society or improvement of safety (e.g. cars). Unfortunately, rising pollution through the use and production of technological artefacts is only one negative effect. This has resulted in a higher responsibility of government, which is often met by limiting harmful impacts of technology by regulations. Thus, companies cannot neglect their environmental obligations[65] by only considering technical feasibility. Furthermore, the growning number of stakeholders with heterogeneous requirements has to be taken into account, especially since the relevance of dynamic factors, such as trends or customer opinions, is higher than in the past due to correlations and is harder to predict.[66] Individualisation of demands from customers and grown availability of technology impose an intensified competition, in which product diversification plays a key role, e.g. range of product models of car manufacturers. A differentiation in distinct product properties can only be achieved if critical properties are explicitly identified early in design processes.[67] This is even more difficult given the rising complexity in product architectures complicating choices to develop and implement new key technologies in a product due to high impact on later product success. Besides influencing the overall success, the complexity of constraints can induce conflicts in potential product properties, to be detected early in product engineering to avoid later iterations.[68]

3.1.3.2 Exogenous Constraints

The need for integrating constraints is underlined by CLARK and FUJIMOTO, who find the emergence of intense international competition with fragmented markets, demanding customers, and diversified and transforming technologies to be driving forces of product success.[69] This perspective is shared by ALBERS and GAUSEMEIER, who outline the consideration of exogenous constraints as essential factor in the definition of a product.[70] As one of multiple taxonomies, HALES and GOOCH differentiate *macroeconomic* (cultural, scientific and random) from *microeconomic influences* (market, resource availability and customers).[71]

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[65] cp. to Ropohl 2009, pp. 16
[66] cp. to Jetter 2005, pp. 13, see also section 3.1.3.2
[67] cp. to Winterhoff et al. 2009, pp. 15
[68] cp. to Eiletz 1999, Albers & Gausemeier 2010, p. 1
[69] cp. to Clark & Fujimoto 1991, pp. 2
[70] cp. to Albers & Gausemeier 2010, pp. 2, see also Meboldt 2008, p. 163
[71] cp. to Hales & Gooch 2004, pp. 31

ULRICH and EPPINGER name *competitive strategy*, *market segmentation*, *technological trajectories* and *product platforms*[72] as perspectives for selecting promising opportunities in product planning.

MÜLLER-STEWENS and LECHNER describe the *analysis of the general environment* as the highest level of environmental analysis. The aim is to identify prevailing trends in a company´s environment likely to have an influence on the company as key future constraints. Trends are complex and multidimensional phenomena, usually have a large scope, impact, are interrelated and linked to a certain context. They become visible if they form the behaviour of stakeholders in a noticeable fashion. Trends are commonly stable, do not happen abruptly, but evolve slowly, such as the growing age of the population. Identifying trends as early as possible gives companies options to react. HALES and GOOCH differentiate segments for analysing trends as *economic*, *political*, *legal*, *social*, *technological*, *ecological* and *random* on macro-economic level.[73] MÜLLER-STEWENS and LECHNER propose a similar classification:[74]

- *Economic:* Factors shaping market of goods and capital, regulating offer and demand, e.g. availability of resources, rate of unemployment.
- *Political/legal:* Factors changing structures of dependency and power, assigning rights in form of law and regulations, e.g. political stability, law on patents.
- *Socio-cultural:* Factors changing values and norms, structure of society, e.g. development of population, structure of age, environmental awareness.
- *Technological.* Factors affecting use and convergence of technologies, value adding processes e.g. product and process innovations, transfer of knowledge.

In the automotive industry, the trend of society towards higher awareness of ecological issues and the conflicting wish for more mobility are currently identified by trend studies. Constraints from the general environment are often difficult to quantify. It is important to tailor them to specific projects and to consider them in objectives.[75]

The *market* for a product to be engineered is another constraining factor, determining existing demands for the product and potentials for success and failure of a project. Main aspects are a market´s size, growth rate, competitive intensity, depth of existing knowledge of a company about the market and relevant technologies, fit with other products and potentials, such as patents.[76]

[72] cp. to Ulrich & Eppinger 2008, p. 38
[73] cp. to Hales & Gooch 2004, p. 31, Müller-Stewens & Lechner 2001, p. 149
[74] cp. to Müller-Stewens & Lechner 2001, p. 149
[75] cp. to Sandström & Ritzén 2009, pp. 44, e.g. Winterhoff et al. 2009, main trends: neo-ecology, individualisation, mobility, see Albers et al. 2010a Albers et al. 2003, Albers & Matthiesen 1998
[76] cp. to Hales & Gooch 2004, p. 44, Ulrich & Eppinger 2008, p. 40

Customers with their individual needs, urgency of needs and their expectations toward a new product make up the difference between markets. Value and appeal of a product to a customer or user has a huge impact on the product´s success. Difficulties lie in identifying what customers want and to predict their dynamically changing expectations. Especially products in which customers have accumulated experiences, expectations are more holistic, complex, demanding and diversified, leading to the necessity for a subtle differentiation of products in that segment. The conversion of rather qualitative customer wishes into technically evaluable objectives imposes a great challenge in early project stages.[77]

Due to the internationalisation of markets and industries, the growing similarity in product concepts and the emergence of global product segments, more *competitive interaction* determines the international stage. It becomes increasingly important that the current and previous behaviour of competitors is analysed to anticipate future actions and to encounter these with differentiated products. Such information is necessary to decide about a product´s basic orientation, which needs to be reflected in its objectives. A product might be oriented to be a technologic leader, cost leader, customer focused or to imitate the competition. Hints on how a product needs to be differentiated to relevant competitors are basic reflections to new product concepts.[78]

In the early project stages it is important to anticipate the general availability of technology potentially implementable in new products for their own as well as for competing companies. This uncovers much of the range of possible actions each company has to set future product properties and to tailor products to demands of customers. This availability largely depends on the continually changing general *technological development*. In past years, the technological environment was characterised by the merging of existing and new technology fields, and by increased knowledge about technologies. Ecological effects play an important role in constraining the use of technologies in engineering.[79] JAFFE et al. state that the rate and direction of technological change impacts on environmental influence of social and economic activities due to environmental problems technologies might create.[80] The course of development of a technology is cyclic. It follows so-called s-curves and develops from low to rapid growth, approaching maturity before reaching natural technological limits and becomes obsolete.[81]

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[77] cp. to Hales & Gooch 2004, pp. 38, see, for example, Rebentisch et al. 2005
[78] cp. to Clark & Fujimoto 1991, p. 3, Wenzelmann 2009, Ulrich & Eppinger 2008, pp. 38
[79] cp. to Gomeringer 2007, pp. 21, Clark & Fujimoto 1991, pp.3, Hales & Gooch 2004, p. 149
[80] cp. to Jaffe et al. 2001, pp. 65
[81] cp. to Clark & Fujimoto 1991, pp. 3, Ulrich & Eppinger 2008, pp. 40

VALERDI and KOHL name the state of maturity as the key constraint for implementation of a technology in projects, since immature or obsolescent technologies need more engineering effort due to involved risk.[82]

3.1.3.3 Endogenous Constraints

Regarding constraints influencing projects from inside the company, HALES and GOOCH differentiate *corporate structure*, *systems* and *strategy* as well as *shared values*, *management style*, *skills* and *staff*. *Resource availability* as a microeconomic influence is also treated as an endogenous constraint in this context.[83]

The *strategy* of a company limits projects regarding clarity of objectives, level of risk taking and innovation potential. Market and competitive strategies set basic, project independent premises for projects. The technologic strategy defines the direction of future technologic projects. An example in the car industry is the development of product platforms as a strategic tool. Such sets of assets allow a variety of derivative products to be developed quickly and more easily but constrain solution freedom of new concepts.[84] *Management style* and *skills* constrain the implementation of objectives in operative work. Management needs to ensure that the work force is optimally aligned to the objectives of a process and contributes with respective commitment, depending on how management is enforced and the resulting working climate. It further has influence on effectiveness and efficiency of the work of design teams. Crucial constraints for a project are also the resources needed to implement a project and its objectives. Basic resource is suitable personnel to elaborate on an initial impetus for a project. The extent to which this elaboration is possible depends on available information e.g. on potential design of a future product. The elaboration of a concept also depends on the technology available or planned in a company or superordinate cooperation. Further constraints are available material and energy.[85] ALBERS also highlights the importance of endogenous constraints on the conduction of engineering projects. He differentiates between the main internal resources as being *information*, the *employees* themselves, *capital*, *material* and *energy*.[86]

3.1.3.4 Implications

This section outlined specifically that the growing ubiquity of technology and resulting demands of society are seen as a reason for growth and diversity of constraints in future products. Regarded approaches coincide in the classification of constraints.

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[82] cp. to Valerdi & Kohl 2004, p. 7
[83] cp. to Hales & Gooch 2004, p. 44, Ulrich & Eppinger 2008
[84] cp. to Ulrich & Eppinger 2008, pp. 38, Hales & Gooch 2004, p. 44
[85] cp. to Hales & Gooch 2004, pp. 40, Clark & Fujimoto 1991, general technological development as exogenous vs. internal technologic availability as endogenous constraint
[86] cp. to Albers 2010, p. 7, see also Meboldt 2008, pp. 178

Definition 3-4: Endogenous and exogenous constraints

Exogenous constrains are classified as environmental (*economic*, *political*, *legal*, *socio-technical*, *technological (trends)*, *ecological*) and market (*technological development*, *customer*, *competition*) constraints.

Endogenous constraints are classified as *strategic*, *(internal) technological development* and *resource-based.*

3.1.4 The Role of Uncertainty

Since not much is known about the product to be defined in early stages, freedom of solution for the designer is at its greatest, but knowledge about the optimal solution remains an area of uncertainty.[87] This lack of knowledge is inherent in situations coping with future issues since knowledge can only be generated from completed facts. Only insights about the future will be beneficial to reduce the solution space during product definition.[88] These can only be achieved if the area of uncertainty (lack of knowledge) is reduced. The reduction of uncertainty in product engineering is relevant to ensure a fulfilment of objectives by the product after being launched and to choose "right" objectives to achieve market success.[89] Hence, it is essential to understand the influence of uncertainty on identifying constraints and generating objectives. Thus this section reviews approaches to role and handling of uncertainty.

3.1.4.1 The Aspect of Future

Any attempt to reduce uncertainty by predicting the future presupposes that the future is fixed and thus known. This notion would offer two possibilities to react on this insight. Either the ability to change the future, but then it would no longer be fixed or not to be able to change it, what might result in desperation.[90] This contemplation gives a hint on the complexity of issues concerned with future aspects. Humans have tried to overcome the issues in building models to structure and handle questions on the future. MASINI identifies three concepts of future. *Prognosis* is based on the past and on analysis of the present. It is to be conducted as scientific as possible to find out what is possible and what is probable. *Utopia* is the ideal model of the world as it should be. Objectives are not clearly outlined but need to be defined by imagination. To effectively "build" a future, these two models need to be combined, by *project building* or *visions* using present value propositions to clarify future objectives.[91]

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[87] cp. to Jetter 2005, p. 3
[88] cp. to de Jouvenel 1967, pp. 19
[89] cp. to de Weck et al. 2007, p.3
[90] cp. to de Jouvenel 1967, pp. 67
[91] cp. to Masini 2007, p. 47

While some try to build models, others resist in believing in established routines for saving effort to look into the future. DE JOUVENEL believes that this behaviour is more incautious than predicting changes by assuming that some events are more likely to happen than others. Even though structural certainty in the development of the future cannot be postulated as given, the activity of prediction done consciously and systematically is nothing more than an intended conduction of an activity inherent to a human's mind. It is helpful to consider, for example, analogies of situations connected not only via causality and dynamics of regarded developments, but also trends, such as the continuous technical progress in the past hundreds of years. The art of looking into the future is about transferring insights about the current state into the future, taking into account the various influences on the way to the future state. [92]

3.1.4.2 General Approaches to Uncertainty

As soon as complete certainty cannot be asserted, i.e. there is more than one possibility and the "true" state, value or outcome is not known, uncertainty is present.[93] This applies especially when the subject of judgment is situated in the future, as "the difference between an anticipated or predicted value (behaviour) and a future actual value (behaviour)."[94] But also there are things about the past and the present not known to the one making a decision.[95] Uncertainty is inherent to the universe but also to design processes. Measurability of the degree of uncertainty is not always given.[96] Due to the ubiquity of uncertainty, various research fields defined classifications for different types of uncertainty (e.g. engineering, physical, social sciences). The classifications share basic thoughts but differ in their focus on certain aspects according to research field or purpose.[97] Selected approaches are discussed to establish a basic understanding of main attributes of uncertainty (Table A-1).

Basic to an identification of uncertainty for a given system is the delimitation of the observed system itself by the system boundary. The degree and nature of uncertainty varies dependent on the point of view from which uncertainty is perceived. HASTINGS and MCMANUS, for example, define uncertainty from the point of view of the system architect (designer). In this case, uncertainties are linked to the knowledge base of the observing person or organisation.[98]

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[92] cp. to de Jouvenel 1967, pp. 20/87/108, see also Gausemeier et al. 2009
[93] cp. to Hubbard 2007, p. 46
[94] Thunnissen 2005, p. 36
[95] cp. to Lindley 2006, pp. xi
[96] cp. to Hastings & McManus 2004, p. 2
[97] cp. to Thunnissen 2005, p. 24
[98] cp. to Hastings & McManus 2004, p.3, see section 3.1.5.4

Before handling uncertainty, the basic task is to understand the *character* and *cause* of the prevailing state of uncertainty to evaluate whether it can be reduced or not. If any information, i.e. fact needed to be known to complete the architecture of a product, is not or only imprecisely known, there is a *lack of knowledge*. This can be information which is not yet gathered, generated or situated in the future. Thus it is reducible. HASTINGS and MCMANUS further perceive *lack of definition* as uncertainty, when uncertainty emerges because things are not decided or specified yet.

Uncertainty related to a lack of knowledge or definition can be called *epistemic*.[99] CHALUPNIK defines *errors* as a further reducible uncertainty, caused by practical constraints, such as lacking financial support to use adequate models or tools.[100] Due to possible changes in the environment of an engineering project (e.g. in nature, human behaviour or technological surprise), the outcome is variable. This variability is inherent, random, unpredictable and can cause multiple different potential outcomes. This is called *aleatory* or *irreducible uncertainty*.[101] Distributed quantities (stochastic terms) can be used as a representation and be modelled mathematically using probability distributions.[102] There has been much discourse in literature if such a thing as aleatory uncertainty exists or whether all uncertainty is caused by a lack of knowledge and is epistemic, i.e. reducible. It is argued that the perception of irreducibility of uncertainty is resulting from a lack of knowledge about underlying fundamental processes. This happens because these processes are principally not understood or because it is consciously chosen not to increase the knowledge about them, e.g. complex physical processes. Supposing an ideal state, methods would exist to gather all knowledge of all uncertainties in a potential project. Since these possibilities are usually not given in a cost and time oriented development environment, it is more efficient to regard realistically achievable knowledge as epistemic and take all which is beyond into account as aleatory uncertainty.[103] THUNNISSEN further distinguishes *interaction uncertainty*, describing uncertainty emerging from interaction of events or disciplines, which potentially could have been or should have been predicted. It includes uncertainty due to disagreements between different agents, who evaluate uncertainty on a subjective level, and the need for new evaluations due to new data. This differentiation is found to be important for complex multidisciplinary systems, with many subsystems, variables and experts involved.[104]

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[99] meaning ”of or relating to knowledge or cognition”, Wiktionary 2010, query “epistemic” (10/08/08)
[100] cp. to Chalupnik et al. 2009, p. 463
[101] cp. to Meijer et al. 2006, p. 223, Chalupnik et al. 2009, p. 463
[102] cp. Thunnissen 2005, p. 39
[103] cp. to Thunnissen 2005, p. 39, Hastings & McManus 2004, p. 8
[104] cp. Thunnissen 2005, pp. 40

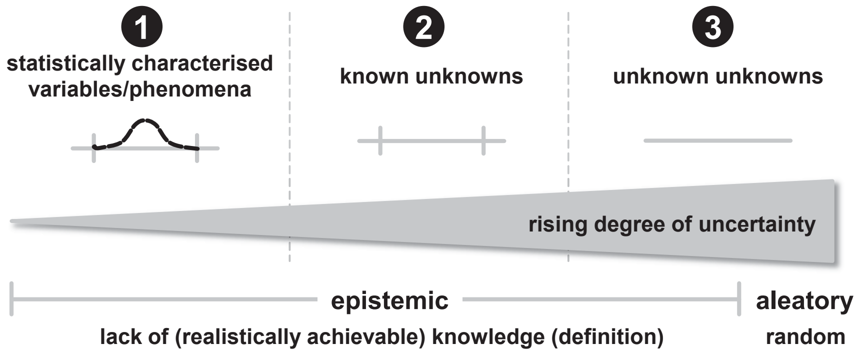

Figure 3-3: Degree of uncertainty[105]

The transition between epistemic and aleatory uncertainty can be modelled by the respective *degree of uncertainty* in a specific situation. Different degrees can be distinguished based on the cause of uncertainty, thus either the level of missing knowledge (epistemic) or randomness (aleatory). HASTINGS and MCMANUS identify three main sections (Figure 3-3). *Statistically characterised variables* i.e. phenomena, which may not always be known exactly, but can be described statistically or at least by boundaries (❶), resulting from linguistic imprecision or approximations. *Known unknowns* can be described in the best case by boundaries, e.g. the observed parameter is known but its value is unknown (❷). Depending on effort to be spent, handling of such parameters proceeds statistically, qualitatively or if possible semi-analytically, e.g. performance of new technologies. *Unknown unknowns* are not known (❸). If possible, conservative mitigation strategies might be applied. The same principle as used in other described sections applies. With enough effort realistically achievable knowledge can be collected to reduce unknown unknowns to statistically characterised variables.[106] If uncertainty is not reducible by realistically achievable knowledge, it is aleatory. The degree of the randomness cannot even be estimated by gathering knowledge. Similarly EARL et al. define known uncertainties as depictable by probability distributions, i.e. putting limits on possibilities. Experiences of past developments may facilitate the estimation of such uncertainties. Equivalently to unknown unknowns, unknown uncertainties are events not at all expected.[107]

As a source of uncertainty, EARL et al. distinguish *uncertainty in description* and in *data*. Uncertainty in description refers to the definition of models used in engineering. Since these are used to make reality manageable, they are always an abstraction for a certain scope of reality. Thus, each description is at least partly false and data can only be gathered for elements included in the scope of the model.

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[105] own illustration, based on Hastings & McManus 2004
[106] cp. to Hastings & McManus 2004, pp. 4, see section 3.1.4.3 for mitigation strategies
[107] cp. to Earl et al. 2005, p. 182

Elements lacking due to the definition of scope increase uncertainty in the results. This type of uncertainty can also result from ambiguity in description.[108] THUNNISSEN classifies this type of uncertainty to be epistemic as *approximation*, *numerical* and *programming errors*.[109] Uncertainty in data results from its state of completeness, accuracy and consistency. An issue causing uncertainty is to create robust predictions using uncertain data.[110] He further identifies *behavioural uncertainty* as epistemic. This includes uncertainty, originating from the way individuals or the organisation act. It emerges from choices in design with several alternatives, requirements generated by multiple stakeholders, unpredictability about what an individual will decide and from errors to be made.[111]

Besides the originating *unit* of uncertainty (description and data), the *location* of its origin may be identified. A main differentiation can be made between the source of uncertainty to be inside or outside the observed system, i.e. being *exogenous* or *endogenous*.[112] The exact delimitation of what is inside and outside the system depends on the definition of the system boundary, dependent on the system in focus and respective scope of uncertainty estimation. DE WECK et al. suggest a typical system boundary by defining endogenous factors to be within greater influence to a designer and exogenous factors to be less influenceable (Figure 3-4).

Endogenous sources of uncertainty are classified regarding the *product context* (e.g. novelty of technology, unknown interactions between product components), the *corporate context* (e.g. the company's strategy, agreements with suppliers) and *use context* (e.g. skills of potential users). Exogenous sources of uncertainty extend this classification to the *market context* (e.g. actions of competitors, environment) and the *political and cultural context* (e.g. fashions and regulations). CHALUPNIK et al. adapt this classification to specify *process* uncertainties. This includes e.g. difficulties of process objectives and their novelty for the company.[113] The different context areas partly overlap, but a lot of endogenous uncertainties are independent from exogenous uncertainties. Different layers can be defined, describing the degree of influence a company has to handle the effects of the respective uncertainty (Figure 3-4). DE WECK et al. outline that common practice in handling these uncertainties is to address them in different models, reconciled with situation specific requirements.[114]

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[108] cp. to Earl et al. 2005, p. 184
[109] cp. Thunnissen 2005, p. 37
[110] cp. to Earl et al. 2005, p. 184 and section on uncertainty in information (section 3.1.5.3)
[111] cp. Thunnissen 2005, pp. 38, see section on decision making and problem solving (section 3.1.5)
[112] cp. to de Weck et al. 2007, pp. 3, Chalupnik et al. 2009, pp. 460
[113] cp. to Chalupnik et al. 2009, p. 462
[114] cp. to de Weck et al. 2007, pp. 4

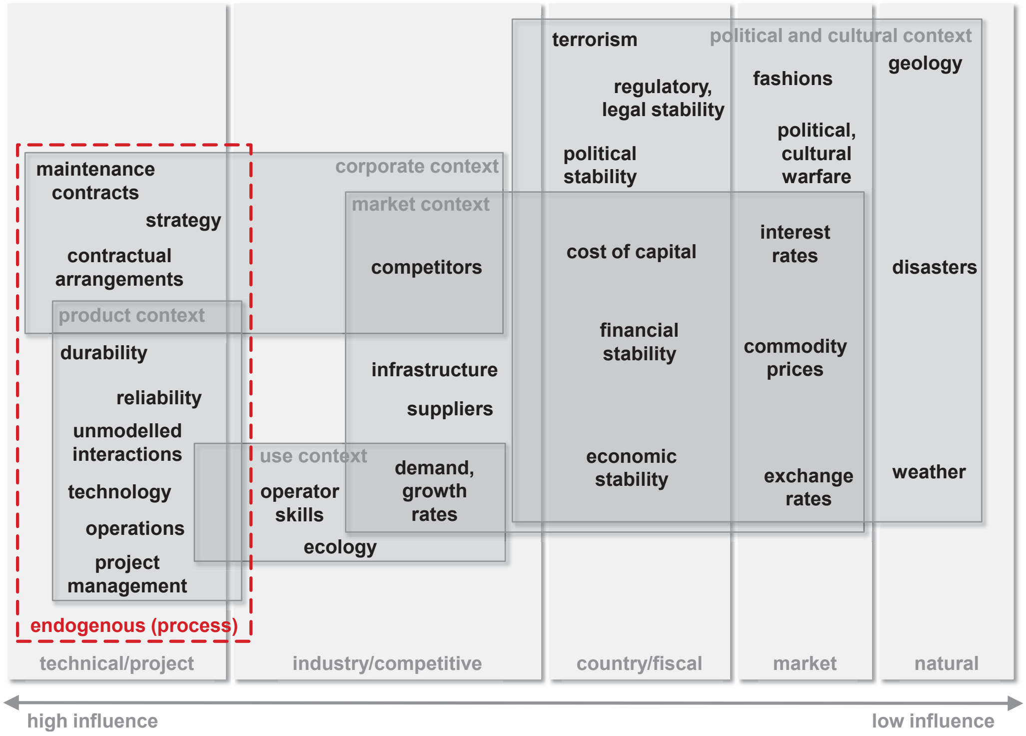

Figure 3-4: Influences of endogenous and exogenous sources of uncertainty[115]

Risk is often mentioned as a direct *effect* of uncertainty. THUNNISSEN describes risk as a measure of uncertainty to achieve an objective respectively to technical performance, cost and schedule. The risk level depends on the probability of occurrence and the consequences.[116] HUBBARD gives a more encompassing definition of risk as “a state of uncertainty, where some of the possibilities involve a loss, catastrophe, or other undesirable outcome.”[117] According to HASTINGS and MCMANUS risk can be quantified multiplying the probability of an uncertain event and the severity of its consequences. Uncertainty may also generate opportunities, equivalently calculated as a probability of event and value. Risks and opportunities can be expressed in a shift of scheduled costs, development time or by external factors, such as shifts of market or user needs.[118] HUBBARD finds organisations usually use risk analysis only for routine operational decisions, but insufficiently for larger decisions with higher level of risk.[119] However, ALBERS and DEIGENDESCH stress that uncertainty is a key risk for innovation projects and needs to be specifically addressed with adequate methods and tools.[120]

[115] based on Chalupnik et al. 2009, p. 461 and de Weck et al. 2007, p. 4/6
[116] cp. Thunnissen 2005, pp. 28
[117] Hubbard 2007, p. 46
[118] cp. to Hastings & McManus 2004, p. 2
[119] cp. to Hubbard 2007, p. 83
[120] cp. to Albers & Deigendesch 2010, pp. 3, Deigendesch 2009, p. 87

3.1.4.3 Handling Uncertainty

Literature provides several strategies to deal with uncertainty; there the one used depends on the prevailing situation, e.g. product complexity, and available resources (effort vs. benefit).[121] Two main objectives of strategies can be distinguished:[122]

- *Reduce uncertainty*. This strategy focuses on the increase of knowledge about the observed system and its environment, e.g. by collecting more information, additional analyses or by decomposing systems into manageable subsystems.
- *Protect the system*. An active protection of the observed system implies its ability to adapt itself to unknown changes. A system is passively protected, if it is able to process unknown impacts without needing to change its structure. This strategy does not aim to mitigate the existence, but impact of uncertainty.

To *reduce uncertainty*, various formal approaches can be used to model uncertainty, e.g. probabilities, Bayesian probability, Dempster-Shafer belief functions or possibility theory, such as fuzzy logic. Such approaches are often not available for designers, due to basic complex formalisms and pressure for quick and cost-efficient assessments of uncertainty.[123] DE WECK et al. propose different practical approaches, which they were able to verify by application to uncertainty issues in the design of systems. They differentiate between the representation of uncertainty as a *continuous variable or* as *discrete events* (likelihood, time of occurrence, magnitude of events) or *scenarios*. Probably the most practical approach is to plan scenarios. It has been implemented in various methodological procedures,[124] but they all focus on defining scenarios to predict potentially different "futures." Based on identifying factors influencing the development, different potential developments of the current state are investigated. They depend on the character of the variables observed and the influencing factors (Figure 3-5). Scenarios focus on qualitative, long-term statements, aiming on considering interactions between influencing factors.[125]

Dynamic developments are also often considered by identifying periodic trends of exogenous constraints to engineering projects and anticipating them for the future. Such assessments of the future are rather qualitative, mid-term statements. Predictions as commonly found on operative level are usually quantitative, aiming on short-term planning.[126]

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[121] cp. to de Weck et al. 2007, p. 11, Hastings & McManus 2004, p. 2
[122] cp. to de Neufville 2004, Chalupnik et al. 2009, pp. 463, see also Müller-Stewens & Lechner 2001
[123] cp. to de Weck et al. 2007, p. 7
[124] e.g. Gausemeier et al. 2009, Siebe 2009
[125] cp. to Siebe 2009, p. 10
[126] cp. to de Jouvenel 1967, p. 206, Siebe 2009, p. 10, see also section 3.1.3.2,

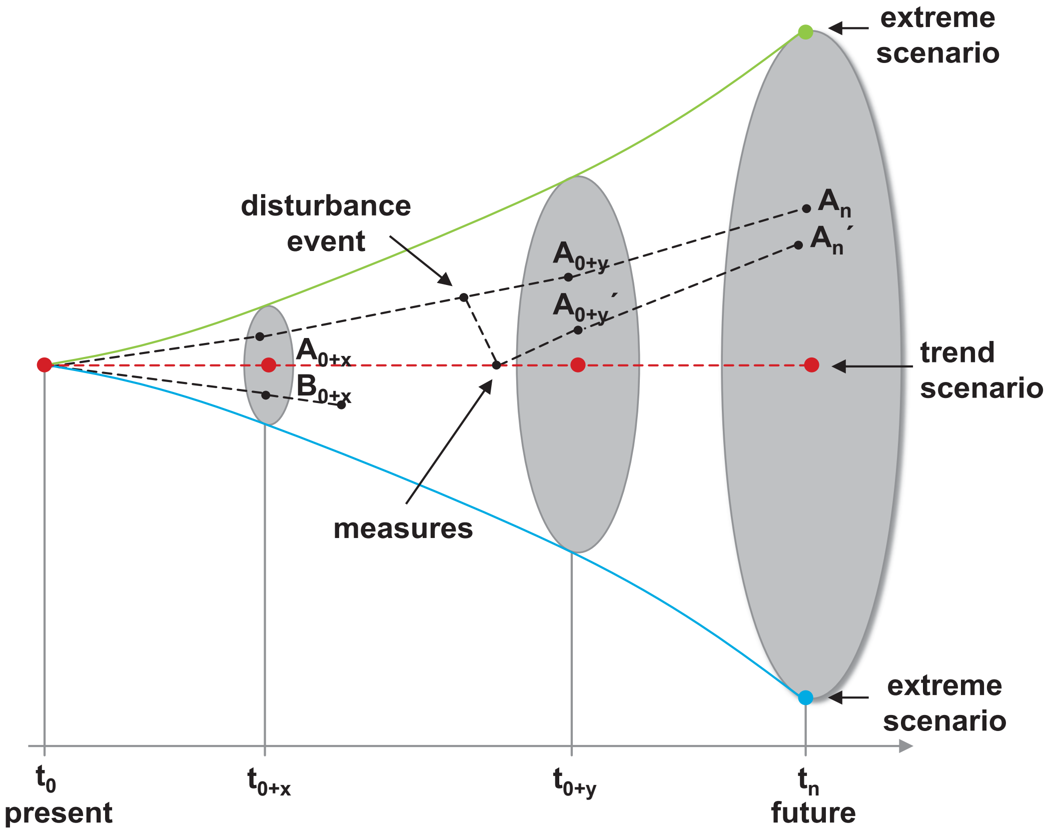

Figure 3-5: Scenario planning[127]

van der Duin and den Hartigh investigated ways of reasoning in different strategic approaches to assess the future. They found that various static approaches fail, since they commonly assume that future is predictable enough to implement strategy, neglecting dynamic aspects and uncertainties. Also, frameworks and methods to support dynamic planning are not yet fully developed.[128] Albers et al. reported positive results using the modelling framework iPeM as an environment for methods, such as scenarios planning and trend analysis to derive product profiles.[129]

A *protection* of the respective system in common engineering practice can be fairly simple, such as imposing a conservative design margin. This results in a solution, which is robust to changes in requirements and the environment.[130] Albers et al. have proposed and verified several approaches on how to increase the robustness of a product by systematic validation procedures throughout the product engineering process. [131] Such approaches address the robust design of the *product* in focus.

[127] based on https://widawiki.wiso.uni-dortmund.de (11/01/10)

[128] cp. to van der Duin & den Hartigh 2007, p. 153, see also Gomeringer 2007

[129] cp. to Albers et al. 2010a, pp. 5, see also Albers & Muschik 2010a

[130] cp. to Hastings & McManus 2004, p. 8, see also literature from research area *robust design*

[131] see, for example, Albers et al. 2010h, Albers & Enkler 2009, Albers et al. 2010e, Albers et al. 2008d, Albers et al. 2007b, Albers et al. 2008d

CHALUPNIK et al. propose different strategies for the robust design of *processes* by increasing[132]

- *reliability:* Passive strategy, the process behaves according to specification.
- *robustness:* Passive strategy, the process aims to achieve the same objectives under uncertainty (high level objectives, e.g. fuel consumption, stay the same).
- *versatility:* Passive strategy, the process is able to meet changing objectives within its given structure.
- *flexibility:* Active strategy, the process is able to adapt its structure to meet changing objectives.

CHALUPNIK et al. favour the application of system protection to the reduction of uncertainty because of the irreducibility of aleatory uncertainty and the high effort for collecting information and knowledge about epistemic uncertainties.

3.1.4.4 Implications

This section discussed approaches on the nature and handling of uncertainty. The reflection of characteristics of the future showed that a systematic and structured assessment of future issues is believed to be possible. It depends on an individual's mental models. Though differing in distinct classification issues, several approaches on uncertainty agree that there is reducible uncertainty mitigable e.g. by applying scenario planning and that irreducible uncertainty requires strategies to protect the system. Thus, this thesis draws on the following classification of uncertainty:

> **Definition 3-5: Uncertainty**
>
> Uncertainty represents a state in which several potential outcomes are possible. It can be reducible (epistemic) or irreducible (aleatory) (*basic character*). Its *cause* can be a lack of knowledge or random and is of particular importance to its actual *degree*. *Sources* can be the description in models or data and be located inside (endogenous) or outside (exogenous) the observed system. Its *effect* (risks, opportunities) can be handled either by reducing uncertainty or by protecting the respective system.

Investigated approaches show the necessity to consider exogenous and endogenous constraints as a potential source of uncertainty in a system. Based on insights from this section it is concluded that uncertainty needs to be further studied as influencing factor in the identification of constraints and generation of objectives, since its actual impact and handling in the context of generating objectives has not been studied yet.

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[132] cp. to Chalupnik et al. 2009, pp. 463, de Neufville 2004, pp. 9, Hastings & McManus 2004, p. 2

3.1.5 Decision Making and Problem Solving

A considerable number of approaches, which deal with objectives, study the role of objectives as criterion for decision problems. This section focuses on approaches discussing objectives in respect to their function of validating decisions in problem solving processes. This excludes approaches considering mathematical optimisation problems since these presuppose an existing decision basis not yet available in the early stages of product engineering as focused on in this thesis. Relevant literature is studied to identify requirements believed to be essential for objectives to best fulfil their role in decision making and regarding issues impeding the generation of objectives complying with the requirements. This section argues that the information and knowledge used in decisions and the decision making individuals themselves constitute a potential uncertainty factor in the generation of suitable objectives.

Looking at the product engineering process from an abstracted perspective, it can be described as a transformation of an *as-is* into a *should-be* state. This transformation is frequently modelled as a problem solving process. Most approaches to describe this process are similar in the main steps to be completed. ALBERS et al. understand problem solving as transforming objectives into objects (product), including the main steps *situation analysis (S)*, *problem containment (P)*, *search for alternative solutions (A)*, *selection of solutions (L)*, *analysis of the level of fulfilment (T)*, *decision and implementation (E)*, *recapitulation and learning (N)*.[133] The individual attempting to solve a problem by using these steps and their mental models are believed to be the key issue in investigations on this topic. DÖRNER studied reasoning, acting and decision making of individuals, who tried to solve a complex situation. He found that people start with the *formulation of objectives* (criteria for evaluating the suitability of measures). They continue with *building of models* and the *collection of information* (linking of information) before proceeding with a *prognosis and extrapolation* of the future state, relevant to the aspired solution of the problem. Then, *operations* are *planned*, *decisions* are *made* and *implemented*. *Effects* are subsequently *controlled* and *actions revised*.[134] The authors agree that these steps may be subject to iterations, due to inefficient conduction of the single steps or changed constraints.[135]

3.1.5.1 The Role of Objectives for Decision Making

Throughout the entire process of product engineering, different solution alternatives are evaluated, selected and decided in individual or team-oriented processes. This decision making process comprises all events in the problem solving process.

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[133] cp. to Albers et al. 2005a, pp. 7, Albers & Meboldt 2006, see Saak 2006 (building on German directive VDI 2221 1993), German acronym SPALTEN, refer to section 3.2.3.2 for more information

[134] cp. to Dörner 1989, pp. 74

Thus it covers all choices and judgements (conscious or unconscious) in product engineering.[136] ROPOHL states that to reason decisions rationally in a problem solving process, it is necessary that arguments are aligned with some kind of objectives.[137] According to ZANGEMEISTER these need to be grounded in a system of objectives of the respective organisation, containing all relevant objectives of particular importance to operations. A contentually incorrect, not sufficient description of objectives may result in wrong decisions. The system of objectives holds a great significance for decision making, providing premises from which criteria for evaluating alternatives can be derived. Its contents include chances, risks of alternatives as well as relevant value dimensions of the decision maker, their motives and restrictions for acting.[138]

Equally, HALL understands objectives and their measurability as a substantial factor in decision making. If measurability is not accounted for, poor value judgements may result. Further factors are prevailing *uncertainty*, *number* of *individuals contributing* to the process as well as the chosen *decision criterion*. The more of these aspects are explicitly considered in decision making, the more difficult a decision gets. All factors are implicitly included in each decision process.[139] BREIING and KNOSALA name requirements as basic requisites for an implicit and explicit evaluation of technical systems and decisions in engineering processes. This is because they serve as the basis for deriving decision criteria. Just as HALL, they state that profound decisions depend on the measurability of the requirements as well as on their *explicitness* (preciseness), *completeness* (dependent on respective project stage), *relevance*, *unified understanding* and available information on specific project and constraints.[140] Engineers often believe that objectives for such decisions are somehow imposed on the project from external institutions.[141] However, each objective has to be subject to a generation process itself. The generation of objectives is characterised by different decision situations in which decision makers with a differing understanding of objectives contribute to the development of an objective.[142]

Concluding, objectives play a significant role in decision making in problem solving processes in product engineering. Likewise, the development of objectives is itself characterised by decision situations ("bootstrapping issue"). [143]

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[135] for further approaches see, for example, Ehrlenspiel 2007, Haberfellner et al. 2002
[136] cp. to Jupp et al. 2009, p. 239
[137] cp. to Ropohl 1975, p. 58
[138] cp. to Zangemeister 1973, pp. 89
[139] cp. to Hall 1962, p. 234/244
[140] cp. to Hall 1962, p. 234, Breiing & Knosala 1997, pp.1
[141] cp. to Ropohl 1975, p. 58
[142] cp. to Eiletz 1999, pp. 25
[143] see section 5.3 for further investigation

3.1.5.2 Measurability of Objectives

BREIING summarise potential types of values of a requirement as:[144]

- *quantitative:* deterministic (counted, measured, weighed, calculated, estimated)
  probabilistic (calculated, observed, estimated*)*
- *qualitative:* linguistic (compared, observed, estimated)

As previously outlined, an ideal objective to be used in decision situations is seen to be *"expressible unequivocally by a set of numbers on a scale having additive units and a natural zero."*[145] BREIING and KNOSALA claim that requirements need to be as quantitative as possible and to be evaluable concerning their range. If necessary, qualitative need to be converted into quantitative values to ensure measurability.[146] This claim stems from the fact that methods to handle quantified values are far more developed.[147] Ignoring objectives not being easily measurable might have a negative impact on evaluating a situation, since decisions may lack a grounded information base. But according to HUBBARD, anything is measurable, independent from its state, if it only increases this information or knowledge base. Causes, that especially long-term oriented information, e.g. regarding strategic objectives, are often believed to be immeasurable, lie in a misunderstanding of measurement concepts, object and method. The concept is that measurement comprises a range of observations reducing uncertainty with the result expressed as a quantity. Thus information and its relationships are needed to reduce uncertainty. It depends on how exactly the object to be measured is defined, for example, by decomposing uncertain parameters into subparts, which are easier to capture.[148]

Regarding the measurement of the values, *identity*, *rank order* and *additivity* are of particular importance for their measurability on different scales.[149]

- *Nominal scales* describe a value as a name or classification, e.g. compatibility to s.th.= yes/no or ecologic friendliness = low/moderate/high (property: identity)
- *Ordinal scales* describe a value as simple order, i.e. values must be comparable and transitive according an attribute. Spacing between ranks is not necessarily equal, e.g. contribution of s.th. to progress = 1./2./3./4./5. (property: rank order)

[144] cp. to Breiing & Knosala 1997, p. 18
[145] Hall 1962, p. 236
[146] cp. to Breiing & Knosala 1997, p. 18
[147] cp. to Hall 1962, p. 236
[148] cp. to Hubbard 2007, p. 5/22/109(/85 citing Charles Handy „The empty raincoat“ 1995, p. 219)
[149] cp. to Breiing & Knosala 1997, Ropohl 1975, p. 62, Hall 1962, p. 151

- *Cardinal scales* are either *interval scales*, describing an ordered set consisting of real numbers, numerically equal differences stand for empirically equal differences relative to the common attribute being measured. Or they are *ratio scales*, in which the ratio of one measurement to another remains equal when the scale is changed e.g. max, min. or range of s.th. (property: additivity)

Quantitative values can be measured as cardinal values, qualitative values on ordinal (e.g. fast, high…) or nominal scales (e.g. y/n). To support the objectivity of measurements, mathematical support can be used. Different procedures can be applied depending on type and fuzziness of the initial state of the objective value.[150]

3.1.5.3 Properties of Information and Knowledge

Section 3.1.5.1 stated that besides measurability, properties, such as preciseness of an objective are believed to be essential to make profound decisions. These are characteristics of associated information to that objective. To be able to assess the suitability of an objective for a decision, the state of information and knowledge the decision maker associates with it, needs to be known.[151] This section studies the state of the art of information and knowledge with a focus on literature to classify and evaluate its main properties. It aims to find indications on properties affecting the formulation of objectives. It argues that information and knowledge associated to an objective occur in different states, influencing evaluation and decision making.[152]

Primarily it is essential to clarify the difference between information and knowledge for the further use of these terms in this thesis. Both information and knowledge represent distinct levels in the evolution of knowledge:[153]

- *Characters* are letters, digits or special characters (e. g. “1”).
- *Data* is a set of characters linked by certain rules or syntax. It is not interpreted yet, such as a number (e. g. “11”).
- *Information* comes into existence if data is brought into context (the growth of sales is 11 %). It is data, which is generated, saved and processed for a specific intention, e. g. for preparing decision situations. Information is always explicit.
- *Knowledge* is information interlinked and complemented with experiences and expectations. It is context specific and depends on individual mental contents and is linked to its owners. In a company these might be customers, employees and the company itself. Knowledge may exist explicitly and implicitly.

[150] cp. to Breiing & Knosala 1997, pp. 31/42, pp. 89, see section 3.1.5.3 for more information on different states in which information on objectives might be available
[151] see also Hubbard 2007, p. 86, Jetter 2005, pp. 30
[152] cp. to Breiing & Knosala 1997, pp.13, Dörner 1989, pp. 74
[153] cp. to Jetter 2005, pp. 32, North 2005, p. 32

According to NORTH, the distinction of knowledge as explicit or implicit is essential for handling it in an organisational context. Explicit knowledge has been articulated, and is therefore disembodied and part of the organisational knowledge base, processable with respective information tools. Implicit knowledge is embodied in subjective intentions and intuitions based on experiences and values.[154] In product engineering implicit knowledge has perhaps the main share of existing knowledge.[155] JETTER outlines the importance of mental models and knowledge of the specific project context for analysis and selection of information, e.g. detecting technological trends in early stages. The corresponding mental procedure used during problem solving is difficult to capture and time intensive to articulate. This is seen to be critical in decision situations, e.g. when evaluating the suitability of product properties to objectives implicitly, while specification documents just depict parts of needed information.[156] To gain advantage from implicit knowledge, e.g. by using knowledge from one project as the basis for the next, processes to transform knowledge need to be considered in organisational practice. Articulating assumptions is believed to help raise awareness about ones own knowledge and to transfer and adapt it to a changing environment.[157] This view is shared by ALBERS, who believes information and knowledge to be a key resource to product engineering processes. An approach is proposed suggesting to link information and knowledge directly to their originating activity in the engineering process. This will ease articulation and handling of knowledge in and increase availability of information across engineering projects.[158]

Subsequently two perspectives are discussed, which literature takes on the evaluation of information and knowledge, namely assessing *quality* and *imperfection*. WANG and STRONG conducted a survey to investigate the *perception* of data quality of actual users of data. They derived a framework with different hierarchical dimensions, capturing not only intrinsic data quality, such as *believability* or *accuracy,* but also dimensions, such as *suitability* of data to its context, *representationality* and *accessibility*. These aspects address ambiguities in data resulting from their form of representation, e.g. in early stages the development of past trends might be differently understood, depending on how it is described.[159]

[154] cp. to North 2005, p. 34

[155] cp. to Mascitelli 2000

[156] cp. to Jetter 2005, pp. 32

[157] cp. to Mascitelli 2000, p. 183, Jetter 2005, p. 34, Nonaka and Takeuchi distinguish four types of knowledge generation and. transformation Nonaka & Takeuchi 1995, p. 72

[158] cp. to Albers 2010, pp. 8, Albers et al. 2010d, pp. 5, see also Albers et al. 2008b, Albers et al. 2008c, Albers et al. 2007a, Albers et al. 2007c,

[159] cp. to Wang & Strong 1996, de Jouvenel 1967, p.192, e.g.: rise of produced cars in % from one period to another (rise decreases), rise in absolute numbers of yearly production (2nd year higher than 1st), rise in absolute number by accumulating yearly production (2nd period higher than 1st)

PRATT and MADNICK studied data quality in respect to *believability* of data. On the basis of findings of LEE et al. they classify believability in three groups. *Trustworthiness* describes reliability of the originating sources. *Reasonableness* captures likeliness of data, including consistency in sources, time and possibility. Interesting in this approach is the incorporation of the temporal context. *Temporality* covers the credibility relating from proximity of transaction, actual validity of data as well as validity of different data values.[160]

Another approach is to assess data by evaluating its *imperfection*. SMETS defines imperfection of data as a result of its *imprecision*, *inconsistency* and *uncertainty*. As inherent properties of the data itself, imprecision and inconsistency are related to the content of data. Uncertainty is caused by a lack of information and triggered by imprecision, which is reflected by the statement: "Often the more imprecise you are, the most certain you are, and the more precise, the less certain. [...] Any increase in one is balanced by a decrease in the other."[161] Form, characteristics and degree of uncertainty in data depends on the imprecision type.[162] One form of imprecise data is *vagueness*, e.g. if the choice between at least two alternatives is left undecided (*ambiguous)*, manifesting in imprecise, not empirically measurable, expressions.[163] Information, such as "company xy will launch a new sports car", can be understood differently, since a sports car might have different properties or designs in different perceptions of individuals.[164] *Fuzzy* information lacks clarity or definition, cannot be expressed by a distinct number and is constrained by unclear boundaries.[165] The information "the fuel consumption of a competitor's car will be close to 7 l/100 km" does not clearly admit decidability whether "close to" means 8 l/100 km or rather 7.3 l/100 km.[166] A further type of imperfection is seen in data, missing but needed to describe an intended circumstance. This can be *incomplete* data, based on errors (*erroneous*, *invalid*), *biased*, *meaningless* or *nonsensical*. SMETS identifies inconsistency in data, if *conflicting* (not compatible), *inconsistent* (not compatible with timely component) or *confused* statements are combined, leading to *incoherent* conclusions.[167] Impreciseness can lead to uncertainty in data, if it cannot be decided whether the content in the data is true or not (partial knowledge of true data value).[168]

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[160] cp. to Pratt & Madnick 2008, p. 3, see also Lee et al. 2006
[161] Smets 1997, pp. 228
[162] cp. to Smets 1997, pp. 227
[163] cp. to Hastings & McManus 2004, p. 17, Thunnissen 2005, p. 40, also linguistic/design impression
[164] cp. to Earl et al. 2005, p. 184
[165] cp. to Bonissone 1997, p. 371, Encyclopedia Britannica Online 2010a, query "fuzzy" (10/08/27)
[166] according to the example in Smets 1997, p. 228,
[167] cp. to Smets 1997, pp. 229, the detailed classification can be found in Table A-2
[168] cp. to Witte 2002, p. 42, Smets 1997, pp. 230

SMETS names objective uncertainty as a property of the data. He classifies it with *randomness* and *likeliness* of an event and *ability* and *necessity* to occur. Subjective uncertainty is linked to the opinion of the observer about the true value based on available data, evaluable regarding *believability*, *relevance* or *decidability*.[169]

The main purpose of tools to handle information and knowledge is to reduce uncertainty for the decision maker. An integrated computer model captures an abstract version of the real world depending on the expected application. Regarding imperfect data, information systems need to uphold integrity in restricting the model or representing the imperfect data. The use of information systems induces additional uncertainty. Uncertainty might arise from measuring, recording, retrieving and processing data. The degree of uncertainty depends on the incorporated model, i.e. rules, structures or matching of information and knowledge to the provided model.[170]

3.1.5.4 Subjectivity and Uncertainty in Decision Making

The ideal decision situation in a problem solving process would demand an entirely quantified list of objectives, decision criteria, evaluable alternatives, knowledge about consequences of these alternatives with potential uncertainties. Only little decisions are in fact made this way.[171] Even though approaches in decision making started to include psychological, organisational and sociological aspects,[172] conditions being described as theoretically optimal and the actual conduction of decision making in practice differ. It is often forgotten that decision making is complex, nonlinear and influenced by various factors, which lead to iterations in the definition of criteria and identification of alternatives.[173] Especially in problem solving processes of product engineering, it is essential to consider these factors besides the actual information for the decision to be made.[174] This section discusses literature, which deals with the assessment of factors impeding optimal decision making. It aims to detect indications on how these factors might affect decisions regarding the generation of objectives. It argues that the outcome of a decision depends to a great extent on the individual, their mental models and perceived uncertainty.

JUPP et al. conducted an empirical study to find out about endogenous and exogenous factors impeding optimal decision making in practice, including aspects, such as design rationale, communication and collaboration in teams.

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[169] cp. to Smets 1997, pp. 230

[170] cp. to Motro 1997, pp. 10, Kwan et al. 1997, pp. 128, refer to Motro & Smets 1997, Grzymala-Busse 1991 for detailed information on handling uncertainty in information systems

[171] cp. to Hall 1962, p. 239

[172] cp. to Wißler 2006, S. 68, Jupp et al. 2009, p. 241

[173] cp. to Jupp et al. 2009, pp. 242

[174] cp. to Hazelrigg 1998

Amongst what they found was that the change of constraints to within a project was a cause of volatility in decision situations. Often objectives with a short-term scope had an influence on long-term implications, which might be caused by the perceived difficulty to generate and integrate predictions for future demands for a product into a decision. As one of the most important factors influencing decision situations they found the suboptimal share of information between the contributing decision makers and a lack of consideration of their differing value propositions. The identified factors affecting criteria, which a decision-maker applies in a decision situation can be summarised:[175]

- *nature of the engineering process*. The interconnectedness of problems, multiple objectives and constraints to a task and their impreciseness as well as risk and uncertainty as inherent characteristics of engineering processes.
- *nature of the environment*: Multiple decision makers often pursue different objectives, differing in inherent value propositions and beliefs as well as skills, knowledge base and information they bring along. Further influences result from the organisational environment, technical constraints (depending on the design issue) and exogenous project constraints (such as environment, competition).

KIHLANDER and RITZÉN found similar results in their empirical study on decision making in early development stages. The study revealed that the difficulty during decision making was rather to be found in finding solutions fulfilling the objectives, than in evaluating design alternatives. Decision making was not *actively* conducted as a process in contrast to decision making processes described in literature.[176]

The previous findings suggest that besides the properties of the information used in decision situations (e.g. impreciseness of objectives), the involvement of the individual as an actor represents another influence on decision making processes. HALL states that human decisions are not made consciously or deliberately at all. A lot of actions to satisfy ultimate needs are made automatically. For conducting a decision, rather simple decision criteria are used such as intuition or an appeal to a respective authority, instead of complicated decision models.[177] Humans are rational only in a certain limit. Some decision makers stop searching for information when they find an alternative is good enough and types of criteria raised differ depending on specific knowledge of the individual.[178] BREIING and KNOSALA find decisions to be solely dependent on deciding individuals, their characteristics and current condition.

[175] cp. to Jupp et al. 2009, pp. 242
[176] cp. to Kihlander & Ritzén 2009, p. 276
[177] cp. to Hall 1962, pp. 239
[178] cp. to Kihlander & Ritzén 2009, p. 268

These factors depend on variable characteristics such as experience, dependent on age, and professional knowledge. The current condition of decision makers depends on their permanent characteristics as impulsiveness or creativity and temporary characteristics as state of concentration or frustration.[179] HUBBARD lists phenomena describing the susceptibility of humans to be biased in a decision situation, e.g. an initial preference for an alternative can be of importance to the final choice.[180] Decision making increases in complexity with individuals involved. The challenge lies in identifying objectives, implicitly of particular importance to each decision maker for their choice and to find a common approach to resolve conflicting objectives.[181]

The prediction of the future state affected by a decision is central to the development of an individual's objectives and decision.[182] Each individual perceives a situation differently. Thus, an individual might be uncertain about a prediction, believing to lack important information or to be unable to identify relevant data. MILIKEN distinguishes three different types of *environmental (perceived) uncertainty*:[183]

- *State uncertainty*: The organisational environment is perceived as uncertain i.e. unpredictable. Future aspects relevant for decisions are not known. Individuals lack an understanding on how elements of the environment are interrelated and how they might change, such as future actions of competitors or general changes, such as developments in technology. The degree of this uncertainty varies according to dynamics and complexity of the environment.
- *Effect uncertainty*: This uncertainty addresses an individual´s inability to predict the impact of environmental events and changes concerning its nature, severity and timing. The individual is not aware of cause-effect relationships. The emergence of this uncertainty is independent from state uncertainty.
- *Response uncertainty*: This is perceived when alternatives for action are not known in a decision situation. The individual lacks understanding about possible response options, their value or utility. Lacking knowledge about potential responses can lead, for example, to an imitation of competitors.

Time and effort spent on resolving an uncertain situation depend on the degree of uncertainty perceived. Most linear models supporting, for example, strategy formulation are not easily applicable in the case of high degree of uncertainty.[184]

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[179] cp. to Breiing & Knosala 1997, pp. 46
[180] cp. to Hubbard 2007, p. 205, further phenomena: *anchoring*, *bandwagon bias*, *emerging preference*
[181] cp. to Hall 1962, pp. 238
[182] cp. to de Jouvenel 1967, p. 147
[183] cp. to Miliken 1987, pp.136
[184] cp. to Miliken 1987, pp.139

SCHRADER et al. find that the degree of uncertainty and ambiguity is not induced exogenously, but depends on an explicit or implicit choice of each individual. Efficiency of the problem solving process depends of the uncertainty level chosen, resources and organisational context. These findings presuppose that an individual´s mental model guides an individual´s problem solving behaviour. Proceeding through the problem solving process implies specifying the values of the parameters of the model. SCHRADER et al. differentiate between the state in which an individual lacks information (uncertainty) and ambiguity (lack in definition of mental model): [185]

- *Uncertainty*: An individual regards a problem and its assigned variables as given, but lacks knowledge about the value of the variables. Uncertainty reduction involves the collection and integration of information relevant to this model and assumed relationships.
- *Ambiguity:* The set of variables potentially relevant are considered as given, interdependencies and the problem solving algorithm are to be determined. A suitable model has to be built, evaluated and verified. A more severe level of ambiguity is perceived if the set of relevant variables is not known.

This differentiation is useful in technological problem solving, e.g. to solve questions about future technologies. If problems are framed as uncertainty, potential solutions are limited to the ones that suit existing mental models. Framing can be induced by the organisation, rules or by elaborating problems using predetermined procedures. Previous successful solutions of a problem reduce perceived uncertainty and ambiguity. Individuals will tend to model their problem scope in a way that suits available information and own problem solving skills. The level of ambiguity and uncertainty perceived by each individual depends on personality, prior experiences, skills and organisational context. SCHRADER et al. conclude that problems and level of uncertainty are chosen, not predetermined. These findings motivate a different handling of problems under uncertainty than under ambiguity. In the first case, a content-specific structure and control measures can be predefined by decomposition of tasks and definition of relationships. Communication networks can be established to support the process. Such structures are robust even to variances of future states if information needed and its use is defined. In the second case, mental models need to be built and verified without knowing tasks of the process a priori. The structure should be content independent. Either the organisational environment adapts to the problem or the framing of the problem needs to adapt to the environment.[186]

[185] cp. to Schrader et al. 1993, pp. 2
[186] cp. to Schrader et al. 1993, pp. 17

3.1.5.5 Implications

This section has examined approaches dealing with the role of objectives in decision making during problem solving. Since objectives are believed to be highly relevant as decision criteria, approaches demand measurable and precise objectives. Literature revealed that these properties depend on the state of information and knowledge, on which the objective is based. Findings outline that besides the form of objectives, the considered content depends on the individual, their mental models and perceived uncertainty. Though stated that the generation of objectives is affected by decision situations, the direct influence of identified deficiencies has not been reviewed.

3.1.6 Implications

This first part of this literature research aimed to investigate how research addresses the consideration of constraints in technical objectives and the issues impeding this process. Section 3.1.1 gave a brief overview of the different understandings of different research perspectives taken on objectives and constraints, arguing that a lacking common approach might be one reason why the identified issue has not been entirely addressed by today's research. The mainly empirical approaches to early stages reveal the relevance of integrating constraints in objectives, but identified peculiarities to that stage have not been investigated in respect to their influence on impeding the generation of objectives. Approaches to constraints are mainly taken by several classification approaches, which indicate the relevance and multitude of constraints and their necessity for being considered early in product engineering projects, but lack any idea of how the different constraining factors in fact find their way to be integrated into the formulation of an objective. Several approaches on classifying and handling uncertainty address the future-oriented character of constraints and objectives, but do not directly discuss the issue of uncertainty regarding its influence on the generation of objectives. The broadest discussion of objectives themselves and their role for product engineering takes place regarding their role as a basis for deriving criteria for decisions. Even though several properties of objectives are being demanded for successful decision making, the actual link between the different states of information building these properties and the formulation of an objective has not been made. Several approaches investigate the role of the individual and their perceived uncertainty on decision making. However, these insights are not extended to describe their influence on how such decisions impact the generation of objectives. Concluding, several research fields address aspects of the identified problem, but none of them takes a holistic perspective to understand what actually happens during the generation of objectives and why there might be difficulties to sufficiently integrate constraints.

3.2 Approaches to Support the Development of Objectives

Besides trying to understand why constraints were not sufficiently considered, the example of the Ford Edsel (section 1) raised the question, how such failure can be avoided in future engineering projects. This section analyses relevant literature to identify requirements seen to be necessary to support and improve the generation of objectives and consideration of constraints. This analysis is twofold. Since objectives and constraints are considered to be interdisciplinary and interrelated, a systemic perspective is taken to analyse systemic theory regarding its means to model the issue and to derive requirements for a systemic description of objectives and constraints in an improvement approach. A view from a product engineering perspective complements requirements regarding suitability of the approach to be implemented in a product engineering environment. Existing approaches are reviewed regarding the fulfilment of the requirements and to identify the latest state of the art and research potential. Thus, this section answers the subsequent questions:

- *The systemic perspective*: What means does systems theory and engineering provide to model objectives and constraints in their respective engineering context? Which requirements result from an improvement approach?
- *The product engineering perspective*: Which requirements are seen to be needed for an improvement approach in a product engineering environment?
- *Modelling approaches*: How do existing specific and holistic approaches, which model objectives and constraints, suit the defined requirements?

This section concludes that systems engineering is suitable to assist in the generation of objectives aligned to relevant constraints. Since existing approaches do not suit identified requirements, a new systemic and holistic modelling approach is needed for an improvement approach in a product engineering context.

3.2.1 The Systemic Perspective

An approach to understand and describe phenomena occurring in complex and inter-disciplinary engineering tasks is systems engineering. It is based on the idea of contextual universality and formal abstractness, using an extensive but structuring perspective, whilst keeping a purposive orientation. It provides mental models and methodologies to solve complex and interdisciplinary tasks.[187] To be able to evaluate the applicability of a systems engineering approach for the prevailing issue, basics from systems thinking are reviewed.

[187] cp, to Patzak 1982, pp. 1

Next, approaches applying this theory to an engineering context are discussed. It is found that objectives and their relationships can be modelled as part of a system, interacting with further systems of engineering. Constraints have not been suitably studied in systems engineering literature.

3.2.1.1 Systemic Comprehension

The following provides a short summary to be able to classify systems engineering as a discipline and highlights its relevance for this research.[188]

Systems thinking bases on systems theory, cybernetics and practical approaches, such as systems engineering and modern mathematics.[189] *Systems theory* dates back to the middle of the last century.[190] One intention of it is to unify theoretical approaches by analysing the isomorphy of concepts and models in different areas and identify useful transformations from one area to another.[191] It builds theory on relations between elements of systems, structure and elements i.e. functions of systems and between subsystems. This theory is used to explain structure, behaviour and influencing parameters of systems to control and depict them in the future. Systems theory provides mental models for each system description.[192]

Cybernetics was founded on the idea to fuse research efforts with similar tasks and issues regarding controlling of machines as well as living beings.[193] The key element to this theory is the open or closed loop. In a closed loop a parameter (controlled variable) is recorded and compared to another (reference variable, specifying the nominal value). Dependent on the result of the comparison, the controlled variable is influenced to obtain an adaption to the reference variable. The difference to an open loop is that disturbances are of less effect on the deviation of the controlled variable, since the basis of the manipulation is the result of an earlier intervention. The theory of cybernetics has generalised this principle to describe human interactions, such as in an engineering project. *Modern mathematics* supports systems thinking with its focus on studying structures and relationships (e.g. set and graph theory).

Systems engineering has evolved from systems theory and cybernetics to satisfy the need for unified methodological approaches for different research areas and industrial applications. It is a collection of mental models, methods and forms of organisation concerned with planning, design and conduction of technical systems in a (socio-) technical context.

[188] more detailed overviews can be found, for example, in Hall 1962, Ropohl 1975, Patzak 1982
[189] cp. to Ropohl 1979, p. 52
[190] see, for example, postulations of von Bertalanffy 1968, Hall 1962
[191] cp. to Hubka & Eder 1996, p. 56 (orig. source: Journal Philosophy of Science (Vol. 22, 1955, p.331)
[192] cp. to Patzak 1982, pp. 11
[193] cp. to Wiener 1948, p. 32, Ropohl 1975, pp. 12

It facilitates complex technical tasks, for example, by switching from holistic to detailed system perceptions or by regarding systems from functional, structural and hierarchical perspectives.[194] Systemic thinking helps to approach issues both from a formally abstract and object independent way. It serves to increase transparency in problem solving to make activities accessible to improvement and documentation.[195] In contrast to conventional engineering methods, it comprises analysis with synthesis and objective orientation. Systemic models and methods can be applied to any technical area, particularly in areas such as the automotive industry where there is a high degree of novelty and rising number of contributing people. In such cases, systems engineering helps consideration of constraints, human interfaces and the need for knowledge in a project.[196]

3.2.1.2 General Description of Systems

In reviewing literature, three different perspectives on systems can be identified. In each, the system is seen as the model of a whole, which can be described by:

- delimitations from environment, i.e. a supersystem → *hierarchical perspective*
- interlinked parts or subparts → *structural perspective*
- relationships between attributes (input/output, states) → *functional perspective*

Together these aspects form a complete model of a system (Figure 3-6).[197] Since they reoccur in various theoretical approaches, they are used as basic classification means to establish a unified understanding for further elaborations in this thesis.

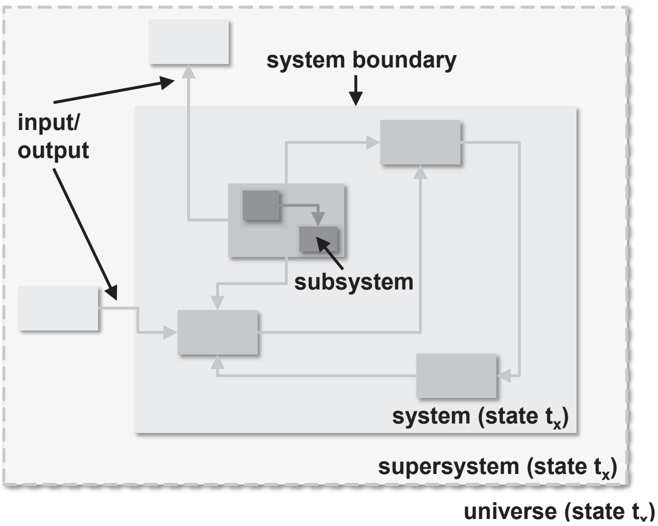

Figure 3-6: System units

[194] cp. to Ropohl 1975, pp. 1/ 53/ 68, Patzak 1982, p. 2
[195] cp. to Haberfellner et al. 2002, p. XVIII
[196] cp, to Ropohl 1975, p. 1, Patzak 1982, p.8/pp. 13
[197] cp. to Ropohl 2009, pp. 75

HALL defines a system as “a set of objects (elements or parts) with relationships between them and between their attributes (properties or qualities). It is embedded in an environment containing other interrelated objects.”[198] Each system contains an unlimited number of elements and is equipped with attributes. Elements are not undividable, but it is not useful to further decompose them in a given context. They are connected to each other by relationships, describing their functional dependence.[199] Attributes are characteristics or properties of a system (e.g. colour, weight). The state of the system itself can also be represented as an attribute. Attributes adopt different values (Table 3-1). Each system is delimited to its environment (supersystem) by its system boundary. The environment is the set of all elements outside the system and is connected at least by one relationship to a system element. A change in the attributes of the environment evokes a change in the behaviour of the system and vice versa. The system and its environment can be partitioned off from the universe as things of interest in a given context. Boundaries to systems are not fixed, but shift depending on the state of problem solving. Two main steps in systems development are the definition of its context (boundary to universe) and environment (system boundary).[200]

Table 3-1: Different values of system attributes

Boolean:	yes/no, 0/1	**qualitative:**	weight = very heavy	**quantitative:**	weight = 200 kg
descriptive:	colour = green	**range:**	weight > 100 kg & < 300 kg		

Functional Perspective

If two attributes of a system are related to each other by linking their values, a function of the system is obtained. An example of functions is the transformation of input into output parameters (e.g. transforming torque in a transmission). The characterisation of a system´s number of attributes and functions means taking a *functional perspective*. ROPOHL states that this perspective is helpful if the focus lies on identifying what a system does rather than what it is (black box thinking). The condition of a system can be depicted by the correlation of the system´s input, output and state as observable from outside. This perspective neglects the internal system layout and highlights behaviour of an entity in its environment.[201] Functions can be described with different notations depending on knowledge about the transformation itself and ability of attributes to be described quantitatively (in mathematical notation).

[198] Hall 1989, p. 54, this quotation names all units of a system similarly covered in most system definitions, for further expressions see Patzak 1982, p. 19

[199] e.g. spatial, temporal or causal, further details in section on the structural perspective

[200] cp. to Patzak 1982, Hall 1962, Ropohl 1975, to Haberfellner et al. 2002, Negele 1998

They can be *descriptive* ("convert torque"), *qualitative* ($M_2 = f(M_1, i)$) or *quantitative* ($F: M_1 \rightarrow M_2 = M_1/i$).[202] To extract a specific function from a given set of system functions or to classify functions of a system, a function analysis has to be carried out. The analysis of functions plays a key part in product development and is itself a large research area on which research effort is spent.[203] For example, ALBERS has proposed the analysis of functions using the C&CM approach, which can be used to describe functional coherence based on systemic principles.[204]

Hierarchical Perspective

When attributes of different systems are connected, the entity of those two systems can itself be regarded as a new system. This system can be described as superior to the two initial systems and is called *supersystem*. The contained systems are called *subsystems*. The *hierarchical perspective* on systems highlights that each system is sub- and super-system in parallel, i.e. that there are multiple levels of entities and parts. These multiple levels form a hierarchy of systems. By moving down a hierarchy a more detailed understanding of the system is obtained, by moving upwards deeper comprehension of its relevance is gained (Figure 3-7).[205] The hierarchical order of systems does not necessarily imply a ranking in the priorisation of the systems.[206] Content, characteristics and level of detail of the subsystems depends on the perspective from which the respective system is analysed.

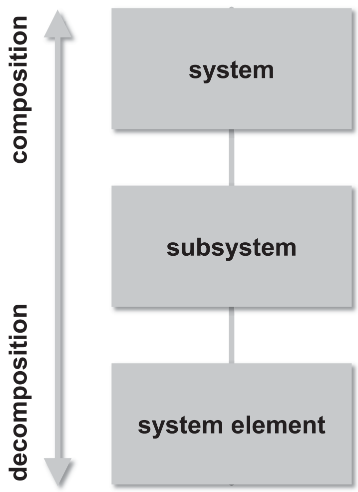

Figure 3-7: Hierarchical structure of a system[207]

[201] cp. to Ropohl 2009, p. 77, Ropohl 1975, p. 26

[202] cp. to Negele 1998, pp. 72, i = transmission ratio

[203] see e.g. Ehrlenspiel 2007 (overview), Steinmeier 1999 (functions in product models), Eckert et al. 2010 (current study on function perception), Alink 2010

[204] see e.g. Albers 2010, Albers et al. 2010c, Albers et al. 2010i, Albers et al. 2009, Albers 2009

[205] see also subsequent section on *emergence*

[206] cp. to Ropohl 1975, p. 30

[207] based on Patzak 1982, p. 45, Bruns 1991

Therefore PATZAK calls subsystems *aspect systems*, considering that each system contains only those elements of the entire system between which relationships exist under the observed aspect.[208] Analysing systems (decomposing a system) or synthesising linkages (building a system) means moving down or up systemic hierarchies.[209] According to ALBERS, these procedures are commonly found in engineering processes, especially during problem solving.[210] JOHNSON finds in part that a system´s structures are given by information from prior knowledge. The designer needs to abstract the system to establish links between highest level and “hierarchical soup” at lower level. These relationships are sometimes estimated, awaiting validation from further information in later engineering stages.[211]

Hierarchies for analysing a system from different levels of abstraction have been found useful when modelling complex systems. Each level has its own set of relevant attributes, laws and principles, thus each level has to be considered independently. Several important characteristics of such *stratisfied* systems can be summarised:[212]

- The choice of levels is dependent upon observer, their knowledge and intention. Some levels are natural or inherent, basic levels are determined by the context.
- The characterisation of one level cannot, in general, be derived from the other levels. The contexts are not, in general, related.
- Each level has its own set of concepts and terms. Interrelations between two levels are studied at the higher level.
- Understanding of a system gets more detailed when moving down the hierarchy and the comprehension of its significance increases when moving up.[213]

Multiple types of hierarchies can be differentiated. ARIYO et al. distinguish:[214]

- *Classification/instantiation hierarchies* in which an abstract unit is defined based on properties that do not change in time. Sub-units are instances of an object.
- *Generalisation/specialisation hierarchies* implement the ‘is a’ relationship. Elements of one class are specialised, sharing some properties with other elements on that specialisation level; other properties differ.
- *Part/whole hierarchies.* Part/whole hierarchies implement ‘part of’ relationships, thus relationships between parts making up a whole (e.g. product models).

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[208] cp. to Patzak 1982, p. 43
[209] cp. to Ropohl 2009, p. 68, Ropohl 1975, p. 30
[210] cp. to Albers et al. 2008a, p. 4
[211] cp. to Johnson 2005, p. 45
[212] cp. to Mesarovic & Macko 1968, p. 30, see also Hall 1989, pp. 63
[213] referring to larger systems and a longer period of time
[214] cp. to Ariyo et al. 2008, p. 737, based on Yoo & Bieber 2008

Such hierarchies can be classified into clusters relating to the factual coherence of the systems attributes and elements. They can be focused on the object, e.g. a topological, temporal or material classification or on the object environment, e.g. tasks. [215] To analyse system structures, further characteristics of a given structure can be evaluated, such as its *reflexity*, *symmetry*, *transitivity* or *coherence*.[216] Hierarchies can be visualised with tree structures, clearly representing nodes within a hierarchy. The steepness needs to be manageable, since a broad structure may not represent important subsystems adequately, but narrow hierarchies require effort and are difficult to manage. ARIYO et al. outline that the principle used for abstraction and the perspective taken, play a role in defining hierarchical levels. Structure building can proceed both top-down and bottom-up, creating differences in the hierarchy. Other visualisation possibilities are, for example, a subordination matrix.[217]

Structural Perspective

As the etymological meaning of *system* suggests, a system can be considered as an entity, consisting of several interlinked parts, the subsystems.[218] Interlinked attributes of subsystems form relationships. Relationships between elements of a system organise the collocation of the elements in a system, implementing the structure of the system. ROPOHL outlines that a view on systems from their *structural perspective* supports an evaluation of system components not detached from their context, but interdependently with other parts of the system. Because of the variety of possible relationships in a system, similar elements may build totally different systems.[219] System´s input and output relationships are *transfer relationships.* Relationships among elements are *coupling relationships*. Transfer relationships correspond to the functional perspective on a system (external structure). Coupling relationships express a link between components (internal structure). This structure can be described from a static or dynamic aspect. *Ordering relationships* are static relationships between elements regarding characteristics of their state (e.g. temporal, spatial, causal, hierarchical (is-a/part-of relation)). They exist in every type of system. Static systems incorporate only ordering relationships. *Flow relationships* describe a relation between output of one and input of another component or environment. This relationship depicts the flow of parameters between elements (e.g. energy, material, information), describing the system´s behaviour.

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[215] cp. to Patzak 1982, p. 43
[216] see Margraf 1987, pp.10, Ariyo et al. 2008, p. 739 for a detailed explanation
[217] cp. to Ariyo et al. 2008, p. 739, Hall 1989, pp. 63
[218] Greek: sýstēma - whole compounded of several parts
Dictionary Online 2010, query “system” (10/09/02)), see also previous section
[219] cp. to Ropohl 2009, pp. 75

An example is an energetic coupling between engine and transmission.[220] NEGELE states that relationships can be defined on different abstraction levels.[221]

BRUNS lists characteristic structures systems may take on from a macroscopic perspective, depending on the application, such as *serial* or *parallel coupling* (e.g. electric systems (series/parallel circuit)), *back coupling/feedback* (cybernetics, control loop) or *hierarchical structures* (previous section). [222] HALL defines characteristics of structures for evaluating their stability and development in time. The *wholeness* or *coherence* of a system describes the nature of the relationship between the system elements. If a change in one element leads to a change in all other elements, the system is called *coherent*. If changes are resisted by the affected element, the total variation in the system is the addition of the variation of all single elements. This state is called *independence* and the system is called *independent*. The move towards independence with time is called *progressive factorisation*. The move towards wholeness, i.e. modifying existing relationships, adding new relationships or elements, is called *progressive systematisation*.[223] Most approaches to build structures depend on the static or dynamic behaviour of the structure. In all cases, the system first has to be delimited from its environment, relationships to the environment need to be detected (external structure), then internal elements and their relationships can be identified (internal structure).[224]

Particularly complex systems, with a large number of elements and relationships, are difficult to visualise. In literature on systems theory and systems engineering, several possibilities are named, such as graphs, matrices or lists. Static structures are often depicted as tree structures or in hierarchies and matrices, dynamic structures as a directional graph or flow charts.[225] Graph theory represents a distinct research area concerned about the description of systemic structures; building on set theory and logical statements. Different types of graphs express different forms of relationships, e.g. symmetric, subgraphs, directional and complete graphs (Figure 3-8). BRUNS recommends the building of graphical structures from left to right and to cluster the structure into areas facilitating an overview. To aid understanding, the number of relationships should match the number of visible arrows. It is helpful to further classify structures hierarchically when they exceed a reasonable number of elements.[226]

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[220] cp. to Patzak 1982, p. 57, Ropohl 2009, pp. 80
[221] cp. to Negele 1998, p. 95
[222] cp. to Bruns 1991, see also Hall 1989
[223] cp. to Hall 1962, pp. 65
[224] cp. to Bruns 1991, pp. 20
[225] cp. to Patzak 1982, p. 22/39
[226] cp. to Bruns 1991, pp. 20

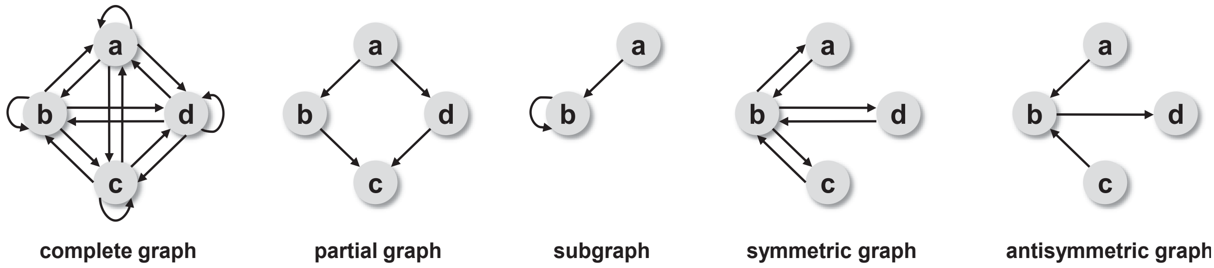

Figure 3-8: Different forms of graphs[227]

System Features

An exemplary classification of main system features of ROPOHL can be found in Table 3-2. Basic features describe a system´s *scope of existence* and *type of evolution* Regarding their relationship to the environment, real systems can influence and be influenced by their environment (*open*). All components of a system emerge after a certain time or change their state in time, e.g. by varying the system boundary due to a change in problem scope, elements, relationships or attributes. Systems can develop to an unlimited number of states (*continuous*) or only to a limited number (*discrete*). Time steps in which changes occur can be *continuous* or *discrete*. The state between discrete changes is assumed to be constant.[228] The system boundary, elements, relationships and attributes may only be formulated or matched within a fuzzy boundary. Such *randomness* can be observed, e.g. for economic conditions.[229]

Table 3-2: Main system features[230]

feature	manifestation
scope of existence	real, abstract
type of evolution	natural, artificial
relationship to environment	closed, open
dependence on time (function)	static, dynamic
dependence on time (structure)	rigid, flexible
distribution of attribute values	continuous, discrete
type of function	linear, not linear
degree of determination	deterministic, stochastic
number of subsystems	simple, complicated
number of relationships	simple, complex, extremely complex

[227] cp. to Bruns 1991, pp. 20, see also Patzak 1982, p. 25
[228] cp. to Negele 1998, pp. 98
[229] cp. to Hall 1962, Negele 1998, pp. 98
[230] cp. to Ropohl 1975, p. 31

According to PATZAK, the *variety* of a system is described by diversity and total number of elements. The *connectivity* of relationships describes the diversity and number of relationships. The *variability* of a system depicts the number of possible states and behaviours depending on the system´s variety and connectivity. It is defined as sum of external and internal variations of conditions (disturbances) minus the variability of a system to react (flexibility and adaptability). Consequently a system can only persist in its environment if it is at least as variable as its environment by being modifiable in response to disturbances (flexibility) or resistant to changed conditions.[231] The discussion on *complexity*, for which numerous authors have derived definitions, is limited in this thesis to the distinction between *complicatedness* and *complexity*.[232] Complicatedness is understood as how a systems´ structure is composed, i.e. diversity and number of elements and relationships. A system is more complex than another if it is more variable, thus it can take on more different states dependent on influencing parameters, e.g. technologic development (product engineering).[233] A system is more flexible, the more potential states it can take on to adapt to a changing environment. Flexibility is a key requirement to systems exposed to dynamic environments. There are different degrees of flexibility:[234]

- *Passive adaptation*: external intervention to adapt the function by changing e.g. prioritisation in a given structure, modification of structure in a given range
- *Active adaptation*: adaptivity of the system, self-regulation of system units to changed conditions. A special case is learning ability: experiences are saved and the system is improved by adaptation based on processing of experiences.

NEGELE outlines that *consistency* requires each hierarchical level to implement a complete description of the system, varying in detail. Information deposited on lower levels may not contradict the higher level. Regarding relationships, this means that if there are two relationships on a lower hierarchical level, at least one relationship needs to exist on a higher level. The direction of this relationship needs to correspond to the subordinate relationships and its type needs to match the two subordinate relationships. The stringency of consistency in a systems description depends on its task. Especially in dynamic systems, not fully described in early project stages, rigid structures hinder the formulation of a system. Potential inconsistencies should be made transparent.[235]

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[231] cp. to Patzak 1982, pp. 22
[232] cp. to Negele 1998, pp. 6
[233] cp. to Wenzel 2002, Negele 1998 (citing Bullinger & Warschat 1996)
[234] cp. to Patzak 1982, p. 27, Hall 1989, pp. 71, see also section 3.1.4.3 on handling uncertainty
[235] cp. to Negele 1998, pp. 94

It is often said that ARISTOTLE first claimed that it is not enough to look at single parts of a system, since the entity of a system is more than the sum of its parts.[236] The challenge in understanding a system and its relevance is about identifying the “more” to its obvious structure. ROPOHL believes that relationships of a system determine its special character (holistic law). The variety of possible networks of relationships between the set of elements impose different attributes of a system.[237] These attributes are what HALL defines as emergent properties (properties of the whole), not easily addressable. Such emergent attributes might not be entirely predictable, since they may evolve from unpredictable interactions of elements or spreading of effects. Emergent attributes exhibited at system level may not be apparent among subsystems. Thus the development and composure of emergent attributes is often not transparent and tangible in contrast to additive attributes, e.g. product weight (summarised across subsystems). Emergent attributes of a system are a sign of complexity. Emergent behaviour of systems should be restricted to intended limits. [238]

3.2.1.3 Systems in Product Engineering

Building on the basic systems theory, this section reviews approaches of systems engineering that are focussed on product engineering. The review draws on the approach of ROPOHL, who has defined product engineering as an interaction of an *operation system* realising a *system of objects*[239] according to a *system of objectives.*[240] The system of objectives is itself influenced by the operation system and the operation system is influenced by the system of objects. The entire system triple is affected by its environment (Figure 3-9).[241]

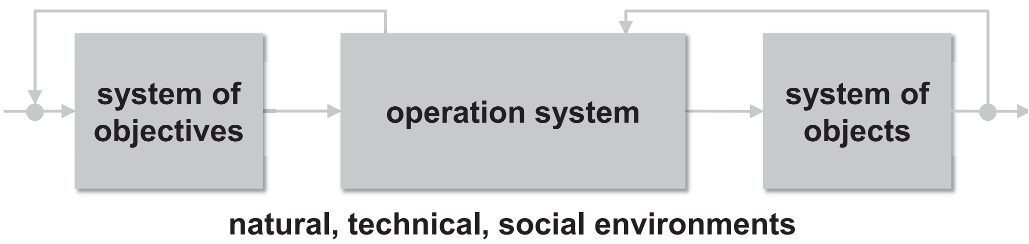

Figure 3-9: Systems of product engineering[242]

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[236] cp. to Aristoteles 1976
[237] cp. to Ropohl 1975, Ropohl 2009, p. 316
[238] cp. to Hall 1989, pp. 56, Earl & Eckert 2005, p. 181, Negele 1998, p. 94, Earl & Eckert 2005, p. 181
[239] Ropohl calls it *system of artefacts* (German = „Sachsystem“). This thesis refers to it as *system of objects* due to the more abstract scope of the term object (e.g. Patzak 1982, Meboldt 2008).
[240] Further works of Patzak (Patzak 1982) or Negele (Negele 1998) adopt this perspective but split the system of operation in two distinct systems, the program- or process system and operation system.
[241] cp. to Ropohl 1975, p. 33
[242] cp. to Ropohl 1975, p. 33

This perspective is enhanced by ALBERS and MEBOLDT, who view the system of objectives and the system of objects as doubly contingent. The final product of a product engineering process is thus a result of the constant correlation between the two systems, coupled by the operation system. Thus, the system triple can be used to describe product engineering processes as complex, adaptive systems.[243]

This section discusses approaches for describing the system triple regarding their applicability to modelling the generation of objectives and constraints. Thus, the focus is on the operation system and system of objectives.

System of Objects

The system of objects comprises developed artefacts, i.e. technical constructs in any form. It includes not only the final product, but also intermediate steps or results on its way to finalisation, such as prototypes or documents. The system of objects is (ideally) finalised, when its state corresponds to conditions described in the system of objectives. Systems of objects are *concrete* (prototype) or *abstract* (models of product), are artificially created by human interaction and influenced from outside (operation system, environment) and inside (relationships between product elements) the system. They are dynamic, developing throughout engineering processes. Interdisciplinary products are particularly complex (e.g. cars). Consistency of elements is vital for proper functioning of the product. Emergent product properties are difficult to predict but important for product success (e.g. quality).[244]

Functional Perspective

The functional structure of systems of objects can be depicted by a transformation of, for example, material, energy or information in space or in time. Thus, the state of included subsystems can change e.g. materially, energetically or concerning its information. For further information refer to NEGELE, PATZAK or STEINMEIER.[245] ALBERS proposes to use the C&CM approach to describe the functional structure of a system, using so called working surfaces (working surface pairs) and channel and support structures to describe the functional coherence of objects and parts of objects.[246]

Hierarchical Perspective

The top hierarchical level of systems of objects is the overall product. Commonly it is classified in its main assembly groups (e.g. powertrain, body, electrics, chassis in a car) and decomposed in line with the product structure down to elementary technical elements (e.g. screws) (Figure 3-10).

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[243] cp. to Meboldt 2008, pp. 155, see also Albers & Braun 2011, Albers 2010, Albers et al. 2010f
[244] cp. to Patzak 1982, p. 33, Ropohl 1975, pp. 33, Negele 1998, pp. 147, Earl et al. 2005, pp. 181
[245] cp. to Ropohl 1975, p.37, Negele 1998, pp.150, Patzak 1982, pp.65, Steinmeier 1999, pp.75
[246] cp. to Albers 2009, pp. 8, see also Albers et al. 2010c, Albers et al. 2010i, Albers et al. 2005b

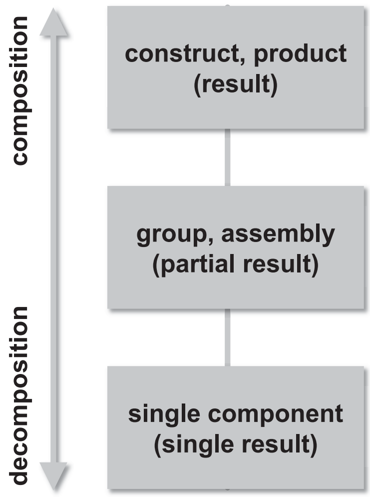

Figure 3-10: Exemplary hierarchical structure of a system of objects[247]

A further division would no longer deal with technical, but microphysical or chemical elements. Elements on subsystems are linked bottom-up using technical means.[248]

Structural Perspective

Several approaches agree that the system of objects has relationships internally to other elements and externally to the system of operation and to the environment. While NEGELE describes a direct connection of the system of objects to the system of objectives (e.g. product properties to which an objective is referenced), the operation system (e.g. which activities work on which components, who is responsible?) and the environment, ROPOHL finds a system of objects is only connected to the operation system from which it derives relevant requirements.[249] The system can take on different structures such as serial, parallel or back coupling. Construction kits are an example for subsystems with suitable interfaces to build superior structures, which avoid integration problems and are adaptable to new tasks.[250] ALBERS and BOERSTING describe an approach to identify relationships between functions and requirements to detect and describe links between parts of objects (components).[251]

<u>Operation System</u>

ROPOHL defines the operation system as incorporating all measures and institutions which contribute to operations in technical work. This includes activities and all participating individuals and groups. Referring to the understanding of systems engineering, such a system is a human-machine system or a *socio-technical system*.

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[247] cp. to Patzak 1982, p. 45, Bruns 1991
[248] cp. to Ropohl 1975, p. 34, see also Negele 1998, pp. 147, Steinmeier 1999
[249] e.g. Ropohl 1975, Negele 1998, pp. 150
[250] cp. to Ropohl 1975, p. 42

The existence of objectives is necessary for the existence of an operation system, since its main purpose is to change its current state to realise the objectives.[252] As previously mentioned, several approaches distinguish between a program or process system as a “system of operations” and the operation system, as a “system, which operates”.[253] Whilst program and process systems contain all operations to be made, processes, events and their relationships, the operation system integrates elements to conduct operations (agents, organisational units, tools and resources).[254] ALBERS introduces the *system of resources* as a subsystem to the operation system, containing all information, employees, capital, material and energy necessary.[255] The following explanations stick to the classification of ROPOHL and ALBERS considering the operation system to containing activities and necessary resources.

The operation system is a system artificially brought into existence by human interaction. By operating, the operation system changes itself, while acting on its environment, being dynamic in its behaviour. Functional and structural collocations in the system are not finally determined and its dynamic development is stochastic.[256]

Hierarchical Perspective

Overall projects, i.e. their processes, can be decomposed down to single activities of a process. Resources can be represented in a multitude of hierarchical structures. Groups of individuals can be classified as hierarchy from society to organisation, with departments as subsystems to the human as smallest element (Figure 3-11).[257]

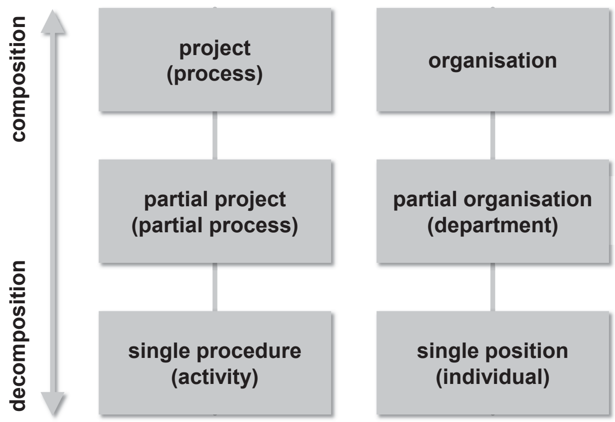

Figure 3-11: Exemplary hierarchical structures of operation systems[258]

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[251] cp. to Boersting et al. 2008, pp. 3
[252] cp. to Ropohl 1975, p. 33/pp. 45, Ropohl 2009, p. 97
[253] cp. to Wenzel 2002, p. 16, Negele 1998, p. 152/162, see Patzak 1982: program and object system
[254] cp. to Wenzel 2002 , p. 43, Patzak 1982, p. 30
[255] cp. to Albers 2010, p. 7
[256] cp. to Ropohl 1975, pp. 100
[257] cp. to Ropohl 1975, pp. 45, Ropohl 2009, p. 97
[258] cp. to Patzak 1982, p. 45, Bruns 1991

Factual operation systems, such as tools, use hierarchical structures, for example, to structure information elements in databases.[259]

Structural Perspective

Activities in the operation system can be collocated using ordering of relationships (e.g. temporal, causal), e.g. conduction of activitiy 1 can be a necessary condition for initiation of activitiy 2 (causal relation). An arrangement of activities with temporal and causal relationships is called *phase* or *stage*. Elements of the operation system can also be connected via flow relationships, like flow of information between activities.[260]

Functional Perspective

ROPOHL defines the function of an operation system to be the modification of its environment and of its own state with the overall aim to transfer requirements from a system of objectives into a system of objects. These functions can run in parallel. A change of the system´s own state is named *internal operation.* An *external operation* takes place when the environment is changed (input/output transformation).[261] WENZEL summarises as input to these activities material, documents, information (system of objects) and control parameters such as objectives, resources, decisions (system of objectives and operation system itself).[262] Outputs are defined as new or modified objects in the system of objects as well as new or concretised objectives.[263] Changes in the system´s environment leading to an adaption of objectives can be considered as a modification of activities and resources.[264] ROPOHL suggests decomposing this general function of the operation system into its constituting subfunctions. These can be clusters of activities or an operation itself. They can be regarded as subsystems to the overall function (operation) of the operation system. He names the subfunctions of the operation system over the course of systems design *stages* (macroscopic perspective). Typical stages in systems design are the *preliminary study*, *main study*, *development and construction*, *production*, *use* and *expiration.* Iterations between these stages are possible.[265] Similar approaches can be found, for example, in PATZAK, HABERFELLNER et al. and HALL.[266] According to ROPOHL, an objective is generated at the beginning of an operation by the operation system. Next, actions to achieve the objectives are planned and implemented.

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[259] cp. to Wenzel 2002 , pp. 17
[260] cp. to Ropohl 1975, p. 49, Wenzel 2002 , p. 85
[261] cp. to Ropohl 1975, p. 48, Ropohl 2009, p. 100
[262] cp. to Wenzel 2002 , p. 85, see also Negele 1998, p. 155/164
[263] cp. to Ropohl 1975, p. 48
[264] cp. to Wenzel 2002 , pp. 17
[265] cp. to Ropohl 1975, pp. 49
[266] cp. to Patzak 1982, Haberfellner et al. 2002, Hall 1962

The result is compared to initially defined objectives. Deviations may lead to a redefinition of objectives or to a replanning of measures.[267] PATZAK names *planning*, *controlling*, *implementing* and *coordinating* (parallel operations) as basic activities of the *purposive-rational operation*. The arrangement of these activities in a control loop (cybernetic system) allows the depiction of corrective measures for deviations of objectives to results (Figure 3-12). The controlling activity may adapt the result (as-is) to objectives (should-be). Planning may modify objectives to suit results. Regarding different hierarchical levels of operations, each activity *implementation* as subsystem can itself be regarded as a controlled system with an assigned control unit. It should be noted that if the degree of detail increases, the scope of planning (long to short term) and the contextual area of validity (strategic, political etc.) decreases. This notion corresponds to the understanding of ALBERS et al. in his interpretation of the problem solving cycle (SPALTEN) (section 3.1.5). Each of the activities of the problem solving cycle involved all other activities on a lower hierarchical level.[268]

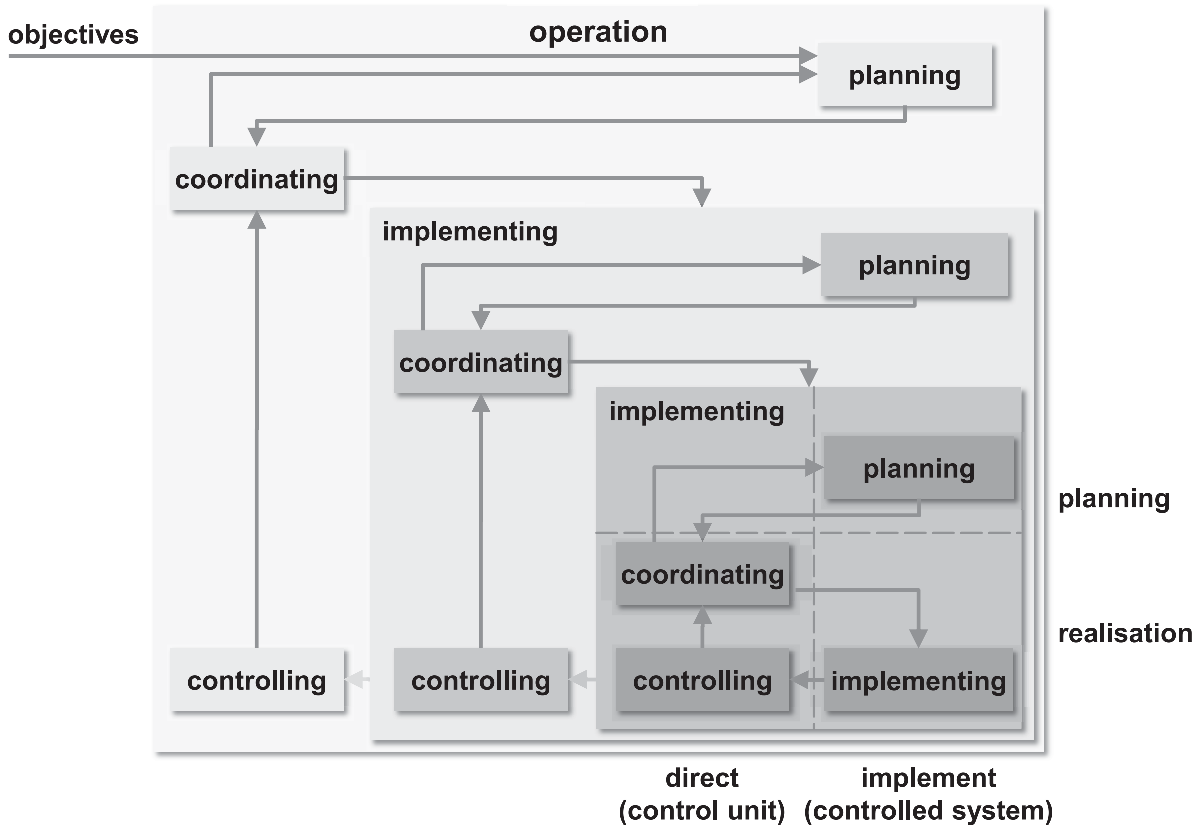

Figure 3-12: Cybernetic and hierarchical model of the purposive-rational operation[269]

[267] cp. to Ropohl 2009, p. 97, p. 100
[268] cp. to Albers et al. 2005a, pp. 4, Albers 2010, pp. 8
[269] cp. to Patzak 1982, pp. 85

System of Objectives

Each engineering task is motivated by objectives, which are a mental anticipation of planned attributes of the system of objects, only to be made accessible by verbal formulation. Objectives are always related to other objectives. This justifies a representation as *system of objectives*. Objectives can be modelled as elements of the system of objectives with attributes having qualitative or quantitative values.[270]

HALL defines it as the ideal system (ultimate functional desirability) based on believed feasibility (physical, technical) and complemented by subjective expectations and wishes of the observer.[271] Referring to ALBERS, systems of objectives contain all objectives, their relationships and constraints to depict an intended future condition for developing the "right" system of objects. It is developed throughout the whole engineering process.[272] HALL outlines the significance of systems of objectives in stating that "it is much more important to choose the "right objectives" than the "right" system. To choose wrong objectives is to solve the wrong problem; to choose the wrong system is merely to choose an unoptimised system.[273] Such relevance for evaluation and selection of product concepts has been widely acknowledged.[274]

Since systems of objectives are mental images of an ideal system, they represent abstract systems. They are artificial, since they need to be actively developed. Systems of objectives are open, but their system boundary is difficult to determine. They are characterised by a dynamic and unpredictable development, since they are constantly confronted with a changing environment. A necessary condition for a successful development is its correct and consistent content.[275]

Structural Perspective

Systems engineering approaches aim to ease structuring and handling of systems of objectives, based on the systemic principle that dependencies between objectives as elements of the system of objectives can be modelled as relationships. ZANGEMEISTER separates *classificatory relationships*, based on ordering characteristics of elements, and *technological relationships*, classified according their mutual influence (Figure 3-13).[276]

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[270] cp. to Ropohl 1975, pp. 33/60, Albers 2010, p. 5, see also section 3.1.5.2 and 3.2.1.2
[271] cp. to Hall 1962, pp. 104
[272] cp. to Albers 2010, p. 5
[273] Hall 1962, p. 105
[274] e.g. Ropohl 1975, Zangemeister 1973, Haberfellner et al. 2002
[275] cp. to Albers 2010, p. 5, Ropohl 1975, p. 58
[276] cp. to Zangemeister 1973, pp. 94/106, corresponds to difference between flow and ordering relation, see subsequent section for classificatory relations

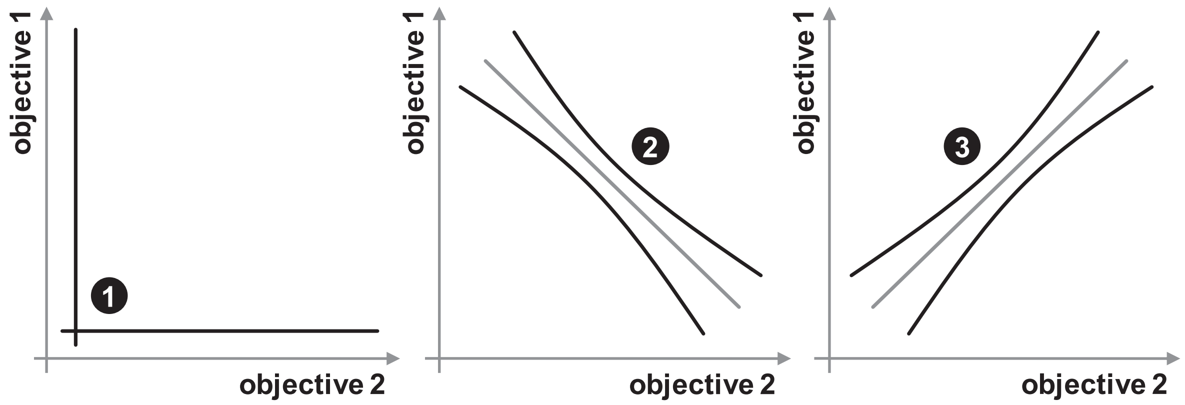

Figure 3-13: Technological relationships[277]

❶ *Indifferent:* Two related objects are totally independent from each other. The fulfilment of one objective has no influence on the fulfilment of the other, e.g. external style requirements vs. requirements on infotainment systems in a car

❷ *Competing:* The more one objective is fulfilled, the less the related objective can be fulfilled, e.g. functional vs. geometric requirements, functional vs. material requirements, differing functional requirements for one component[278]

❸ *Complementary:* The more one objective is fulfilled, the better the related objective is fulfilled. This relationship is symmetrical if the direction of influence can be exchanged with the same effect, e.g. the less drag a car has, the less fuel it will consume (c_w x A ↓ → B ↓, non-symmetrical).

If the first objective has a higher impact on the fulfilment of a third objective than the second one, the fulfilment of the first objective is regarded as more important than the second one. This is called a *preference relationship*.[279]

The treatment of conflicting objectives has been studied by various researchers. Due to the scope of this research work, this discussion of this issue is limited.[280] PATZAK proposes to deal with conflicting objectives by considering competing objectives concurrently with respect to their relative importance (main/side objectives) (*compromise*). Another strategy is to only take into account the objective considered to be most important. If necessary, the second most important objective needs to be evaluated (*dominance of objectives*). Another possibility is to consider all competing objectives, but at different points in time by different people (*schism of objectives*).[281]

[277] Ropohl 1975, p. 58, p. 65
[278] cp. to Braess 1992, p. 17 (includes more examples)
[279] cp. to Ropohl 1975, pp. 64, Ropohl 2009, p. 153, Patzak 1982, pp. 169, Zangemeister 1973, pp. 94
[280] see Eiletz 1999 for further information
[281] cp. to Patzak 1982, pp. 171

Hierarchical Perspective

To order objectives in their respective system requires looking at the specific parts in detail. Thus, a *hierarchical perspective* is taken. Classificatory relationships are commonly regarded from a *vertical* and *horizontal perspective*. A common procedure to classify objectives vertically is to discern objectives and means (❶, Figure 3-14). An objective is seen as a means to achieve a superior objective, which is itself seen as means to a superior main objective. A hierarchy results, in which not all levels are distinct, since elements resulting from one parent do not necessarily have to be on the same level(❷).[282] ZANGEMEISTER suggests a further classification of objectives regarding organisational relevance, e.g. companywide, teams and individual (❸).[283] Other approaches structure technical objectives respectively to their corresponding object in the system of objects.[284] HALL reminds us that the system of objectives is always to be used as a whole. Improving an entire physical system corresponding to a subset of objectives would prove suboptimal due to the objective's relationships.[285]

The horizontal classification of objectives depends on the system's purpose. ZANGEMEISTER names characteristics according to which elements can be arranged, providing a good overview of classification types often found in literature. The differentiation into *main and side objectives* serves to determine the relative weight of objectives. It can help to control completeness of side objectives to fulfil main objectives and to ensure no redundancy. *Objective sections* and *objective types* (❹) can be defined characteristic to a specific organisation or project (*functional aspects*), depending on the specific application or context, e.g. *economical objectives* (e.g. market, costs), *technical objectives* (e.g. performance, quality).

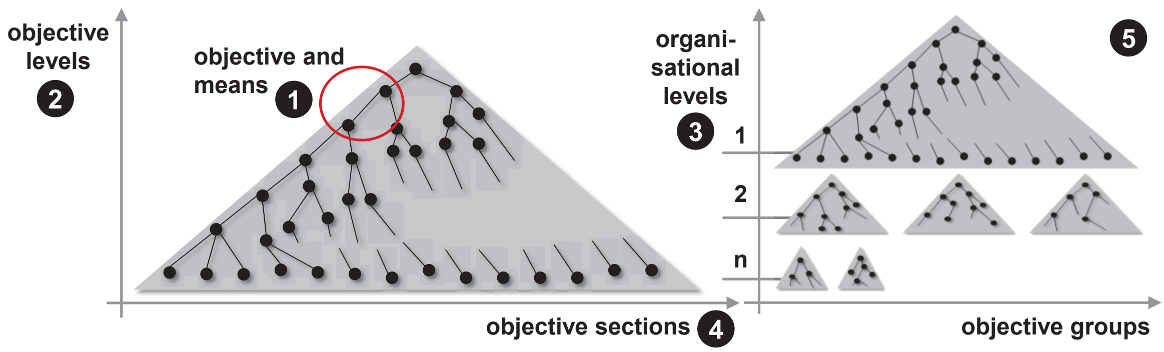

Figure 3-14: Classification of systems of objectives[286]

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[282] cp. to Patzak 1982, p. 159, see also Ropohl 2009, Haberfellner et al. 2002,, Zangemeister 1973
[283] cp. to Zangemeister 1973, pp. 107
[284] cp. to Negele 1998. p. 146
[285] cp. to Hall 1962, p. 106
[286] Zangemeister 1973, pp. 113

Objectives can also be classified according to their *factual context*, particularly for evaluations at a project level, such as product segments (e.g. utility vehicles vs. passenger car), production series (e.g. sports car vs. SUV). The classification of *operationality of objectives* discusses how clearly a benefit of an objective value is derivable from its formulation, helping to determine the residual effort for operationalising the objectives to obtain a basis for evaluation. Eventually, objectives can be classified regarding their *temporal scope* (short to long term objectives).[287] HALL finds, despite the uniqueness of systems of objectives there are recurring subjects to which objectives can be matched. Among these are *profit*, *market*, *quality*, and *performance*, objectives affecting *competitors*, *simplicity*, *safety* and *time*.[288] Horizontal and vertical classifications of objectives define a macrostructure (❺).

Functional Perspective

To discuss approaches to modelling the system of objectives and its embedding in the system of product engineering, the functional perspective is used. According to HALL, a value system represents the logical basis for designing a physical system.[289] The state of the value system depends on the physical system and vice versa. The value system will not be complete until consequences have been identified by realising the physical system and are evaluated in the value system (Figure 3-15). This corresponds to the control principle of an adaptive control system in which inputs need to be matched.

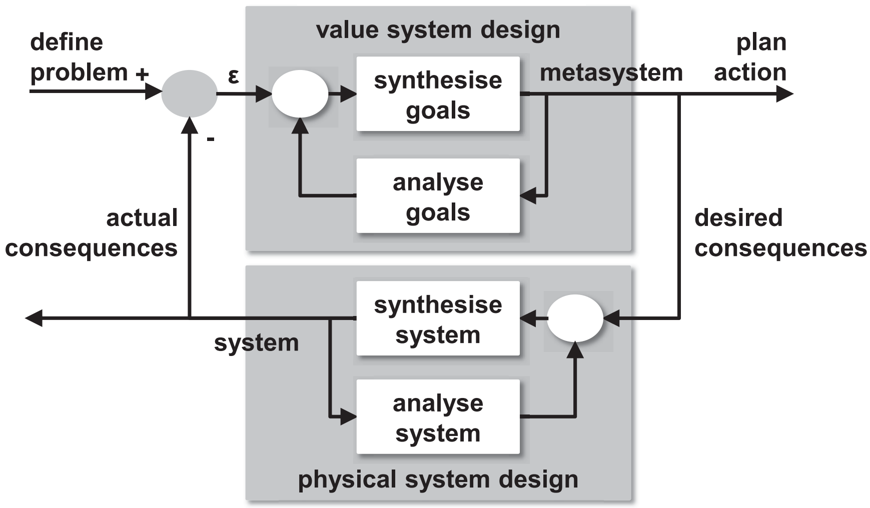

Figure 3-15: Relationship value systems and concrete systems design[290]

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[287] cp. to Zangemeister 1973, p. 109, see also Ropohl 1975, pp. 61, Haberfellner et al. 2002,

[288] cp. to Hall 1962, p. 105, see reference for the complete list

[289] Value systems are seen as equal to systems of objectives, physical system to systems of objects.

[290] cp. to Hall 1989, pp. 105/161

Input to the value system requires additional information beyond the factual data from the physical system, including facts about the current environment, such as legal, technological or social constraints and the need for a physical system (customer). To obtain objectives, this state is to be projected to the state of the final environment, anticipating changes.[291] Objectives are built deductively by resolving superordinate objectives into subobjectives and inductively by collecting and fusing objectives. This cycle ends, "when the difference between what was expected (the objectives) and what has been achieved is smaller than some pre-chosen value (also an objective)."[292] ROPOHL finds the operation system related to the system of objectives in unfolding, analysing, concretising and modifying its structures and hierarchies.[293] NEGELE states that operation systems deliver input to systems of objectives by processes affected by or responsible for objectives. Output of a system of objectives relates to environment, system of objects, operation system and own elements.[294]

Requirements for Designing Systems of Objectives

Approaches discussed, regarding modelling systems of objectives, show that procedures should be flexible and should anticipate modifications at the right point in time. HALL summarises several suggestions for designing value systems (Table 3-3).

Table 3-3: Requirements for modelling systems of objectives[295]

articulation	explicit, conflict free and agreed on formulation
dimensions	find objectives on the same hierarchical level, different system dimensions
consistency	lower level consistent with higher level, logical consistency on same level
concretisation	completeness of the value system, inclusion of experience due to uncertainty
measurability	highest possible level of measurement, ranking by relative importance
uncertainty	account for risk and uncertainties (decision criterions)

3.2.1.4 Implications and Requirements

This review discusses approaches to evaluating the suitability of systems thinking for modelling and improving the generation of objectives. It shows that objectives can be modelled as systems and their interdependencies by using a structural perspective. Objectives can be classified by hierarchical perspectives and interfaces to the engineering context can be modelled by a functional view on the entire system.

291 cp. to Hall 1989, pp. 96/104, cp. to the control loop of operations in the previous section
292 Hall 1962, p. 83
293 cp. to Ropohl 1975, p. 67
294 cp. to Negele 1998. p. 146
295 based on Hall 1962, p. 104

Different approaches depict interfaces to the system of objects or to the environment, but the interface to the operation system, essential for the generation of objectives and the consideration of constraints in the system, has not been explicitly modelled. Requirements identified for an improvement approach are summarised in Table 3-4.

Table 3-4: Requirements for a systemic improvement approach

holistic model	A complete and coherent description of the generation of objectives requires a depiction of system of objectives, operation system and system of objects, their interfaces and the interface to the environment.
generic modelling framework	A generic framework is needed to exploit the potential of systems thinking to ensure general applicability, providing basic unified elements that can be described form different perspectives and levels of abstraction.
system flexibility	Complexity handling due to a stochastic and dynamic development of the environment requires a transparent description of system elements, relationships, attributes as well as structural stability and flexibility.
system operationality	Building and adaptation of system structures needs to be supported by the provision of a comprehensive visualisation approach

3.2.2 The Product Engineering Perspective

The following sections review requirements, proposed by relevant publications in literature, to be considered when trying to improve product engineering processes.

3.2.2.1 Characteristics of Product Engineering Processes

Much research has been spent on investigating processes to identify improvement potential and to develop suitable models to increase operative work efficiency.[296] Most of this research is focused on business processes, whose characteristics are quite different to product engineering processes. To develop suitable modelling approaches for product engineering, these differences need to be considered:[297]

- *Uniqueness:* Product engineering processes intend to do something new, once. Business processes in turn repeat the execution of the same thing.
- *Verifiability:* In contrast to business process activities, the outputs of product engineering activities often cannot be verified directly after completion.
- *Multidisciplinarity:* Product engineering activities are highly multidisciplinary with various interdependencies between activities. Business processes are usually concerned with performing one function.

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[296] e.g. Scheer 1998, Dutta & Manzoni 1998, this research work understands a process as “an organized group of related activities that work together to create a result of value.” (Hammer 2001)

[297] cp. to Browning et al. 2006, p. 114, see also Albers 2010 and Albers & Gausemeier 2010

- *Parallelism:* Product engineering activities are generally conducted in parallel. Business processes activities are commonly conducted sequentially.
- *Transparency:* Dependencies between activities in product engineering processes are more difficult to identify.
- *Uncertainty:* Product engineering processes are exposed to higher uncertainty and incorporate ambiguity as well as risk (see section 3.1.3 on uncertainty).

ALBERS et al. stress *uniqueness* as a central characteristic of product engineering processes to be considered in any model. Many modelling approaches neglecting this issue fail to depict the dynamic behaviour of product engineering activities.[298] WYNN et al. identify a further important characteristic that product engineering processes are self-regulating systems. Their approach proposes that engineering process models need to contain mechanisms able to control the impact of exogenous and endogenous changes.[299]

3.2.2.2 Types of Models

There are numerous proposed models and classifications in product engineering. The classification of WYNN and CLARKSON distinguishes different types of models: [300]

- *Stage versus activity based models.* Stage based models are characterised by a serial and chronological sequence of process steps. Activity based models represent problem solving activities, being cyclical due to rework iterations. Other models integrate the two approaches in a matrix.[301]
- *Abstract versus analytical versus procedural approaches.* Abstract models contain a generic description of engineering processes separating them into few activities to capture a broad range of design situations. Analytical approaches are project oriented, using a representation form to describe the specific project part and methods or tools using the representation for application in execution. Procedural models are more specific, use more stages, usually address a certain type of user but are one dimensional in modelling process sequences.

BROWNING et al. differentiate between *descriptive* and *prescriptive* modelling approaches. Transforming implicit knowledge about how activities are conducted in reality into a model representation is illustrated in a descriptive model approach, built inductively. Prescriptive models are built deductively and focus on improving distinct parts of design projects by giving advice on how to proceed in certain situations.[302]

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[298] cp. to Albers et al. 2010b
[299] cp. to Wynn et al. 2010, p. 514
[300] cp. to Wynn & Clarkson 2005, see also Wynn 2007 for complete classification
[301] see also Blessing 1994, see the approach of iPeM, section 3.2.3.2
[302] cp. to Browning et al. 2006, pp. 115/105 (citing Hazelrigg 1999)

3.2.2.3 Applicability of Product Engineering Models

Besides considering the characteristics and types of product engineering models, the purpose for which a model is built is essential for its applicability within a given context. BROWNING and RAMASEH address the main purposes of engineering models in a taxonomy based on an extensive literature survey:[303]

- *planning of projects:* make commitments, choose activities, structure process, estimate, optimise and improve variables (e.g. cost, time), allocate resources
- *execute/control projects:* monitor commitments, assess progress, redirect, plan
- *visualisation of projects:* action, interactions, commitments, customised views
- *development of projects:* continuous improvement, organisational learning, knowledge management, metrics, compliance

The purpose of *development of projects* is not sufficiently addressed in current literature. It incorporates all tasks supporting better fulfilment of the stated purposes. *Continuous improvement* is concerned with finding out about problems, unnecessary activities and impact of potential changes. *Organisational learning and management* addresses the use of models for assigning information to activities in order to store experience for reducing uncertainty in subsequent projects. *Compliance purposes* include documentation of processes e.g. for process audits. BROWNING et al. find that models developed for one of the listed purposes are often not very helpful for the other purposes. Still, models are misused for another than their intended purpose. They further conclude that the divergence between modelling frameworks in research and models in practice is due to the variety of model users and needs.[304] VALERDI emphasises the necessity to account for organisational factors as potentially impeding the use of models in practice. As critical factors to successful adoption of a model he summarises the need for a *well-defined purpose or reason, ease of use, low risk of failure* and *institutional*, i.e. *administrative advocacy and commitment*.[305]

To integrate multiple models for different purposes, BROWNING et al. propose a generalised framework for process modelling. A modelling framework is defined as “a generic approach which may be applied to modelling any situation within its scope, but which in itself provides only general insights.”[306] Using this framework, models can be derived for specific purposes, constrained by the premises of the framework.

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[303] cp. to Browning & Ramaseh 2007, p. 219, covers suboperations *planning*, *controlling*, *execution*, *coordination* in purposive-rational operation, which need support by process models (sec. 3.2.1.3)

[304] cp. to Browning & Ramaseh 2007, p. 232, Browning et al. 2006, p. 111

[305] cp. to Valerdi 2008, p. 8, see for complete list factors

[306] Browning et al. 2006, p. 111

3.2.2.4 Implications and Requirements

Based on the insights from this section, the following requirements need to be considered for improvement approaches in a product engineering context:[307]

Table 3-5: Requirements for an improvement approach in a product engineering context

transparency	make dependencies between activities explicit
situation specificity	ensure handling of uncertainty and adaptability to changing constraints
intended purpose	enable project planning, execution, control and visualisation
store experience	enable assignment of knowledge to activities
continuous review/ improvement	ensure possibilities to constantly review and improve the process model due to changing constraints
use context	ensure applicability from the adopter perspective, cover all users/needs

3.2.3 Relevant Approaches

The following sections review product engineering approaches related to modelling and improving the generation of objectives with regard to their suitability to fulfil the defined requirements. This analysis of important approaches from the state of the art focuses on the identification of deficiencies in existing procedures.[308] It argues that neither specific nor holistic approaches provide enough functionality to flexibly model the generation of objectives under consideration of constraints. The integrated product engineering model (iPeM) of ALBERS is found to be best suited to the defined requirements and is chosen as the basic modelling framework to elaborate the approach in this thesis.

3.2.3.1 Specific Approaches

This section studies approaches from research areas concerned with development of objectives regarding their suitability to fulfil the defined requirements.[309] It is found that specific approaches mainly depict necessary steps as a sequence on an abstract level with focus on assigning distinct methods for eliciting objectives. Generic (systemic) frameworks to model constraints, objectives, relationships and assigned activities flexibly, situation specifically and consistently during the entire process of generating objectives have not been found.

[307] cp. to Browning et al. 2006, p.106, Wynn et al. 2010, p. 514/519, Valerdi 2008, p. 10
[308] for extensive evaluations on product models refer to see Browning & Ramaseh 2007 or Wynn 2007
[309] for research areas see section 3.1.1.1

EILETZ has made one of the first attempts to extend the methodologies of integrated product development with an approach to designing a process for the identification of systems of objectives and concepts.[310] He suggests a definition of the process to generate and treat objectives with an interface to the concept development process as the basis to describe ideas of his research focus (objective conflicts, focus automotive industry). He subdivides the generation and treatment of objectives in subtasks to which he assigns suitable methods. For the generation of objectives, these tasks are, for example, the *formulation of the subject of the objective*, the *search for and anticipation of requirements* and the *structuring and complementation* of the system of objectives. Ideas from systems engineering are only adopted for structuring the phases of the development process.[311] Despite emphasising that tasks are dynamic, iterative and not sequential, the approach only offers sequential matching of activities to generate different types of objectives (strategic, operative, detail) for each of the main stages of the systems engineering phase model. Flexible modelling of constraints, listed as *company*, *society*, *customer*, *predecessor* etc., and their relationship to the system of objectives and the objectives themselves is not possible. This limitation is due to the one-dimensional representation of the requirements list and that the consideration of constraints is not elaborated, but only suggested to be done systematically by comparing them to relevant objectives.

BADER has developed an approach to manage *product objectives.*[312] He distinguishes between objectives relevant for the *design of the product*, such as regulations, form parameters and *objectives of customers*, such as design, driving dynamics or comfort. He defines the main activities of the management process as *generate*, *plausibilise*, *agree on* and *maintain* objectives. This generation is described as the *identification of objective areas*, *generation of properties* and *determination of values*.[313] The first activity serves to position the entire product in the market, while the generation of properties aims to identify product properties in a so called master system of objectives. The values of properties can then be specified by integrating influences from exogenous constraints, such as competition and internal constraints. These can be used to derive project specific values for customer objectives. Even though the approach suggests a systematic and situation specific consideration of constraints, modelling of objectives, constraints and relationships is not flexibly supported (due to the one dimensional list of objectives). Proposed process models are rigid, sequential and not linked to objectives.

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[310] cp. to Eiletz 1999, German = “Ziel- und Konzeptsystemfindung”

[311] according to the model of Daenzer and Huber 1992, cp. to Haberfellner et al. 2002,

[312] cp. to Bader 2007

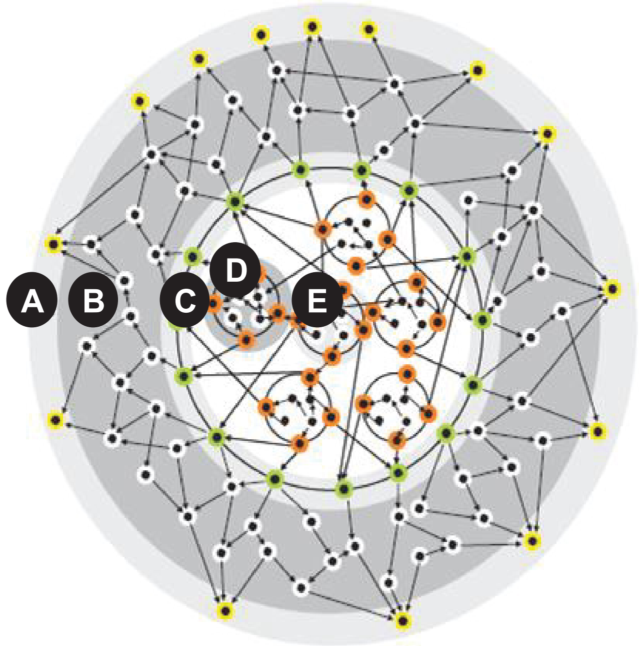

Figure 3-16: Influence network:(A-B) environment (C) requirements (D-E) concept/decision[314]

DÜNSER studied influences of (technical) attributes on objectives, claiming that there are influences between all (technical) attributes of a product leading to an *influence network* (example, Figure 3-16). Influences from the environment (A-B) are directed to the attributes of the future product recognised by the environment (C, e.g. a car´s fuel consumption). An influence network can be used to trace changes in attributes. The network changes with every engineering activity, leading to a change in interlinked attributes. The influence between attributes is measured with the *degree of influence*, quantified relative to a *reference state*, and can occur as negative or positive influence. Thus, the resulting change of each attribute due to its linked influences can be accumulated. The network is unique for each product. Regarding environmental influences, DÜNSER focused on customer related influences.[315]

Requirements engineering has evolved mainly from software engineering. HOOD et al. distinguish approaches in requirements engineering from approaches in requirements management. While the former cover the "engineering" of requirements, the latter addresses the monitoring of the developed requirements.[316] HOOD et al. identify two main activities in requirements engineering, *definition of scope* and *definition of requirements*. *Elicitation*, *specification*, *analysis* and *review* are modelled as iterative activities for defining requirements (Figure 3-17).

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313 German = Zielfelder bestimmen, Zielmerkmale generieren, Zielausprägungen festlegen
314 Dünser 2004, p. 35
315 cp. to Dünser 2004
316 cp. to Hood et al. 2008, p. 32/35, POHL uses *requirements engineering* for both aspects

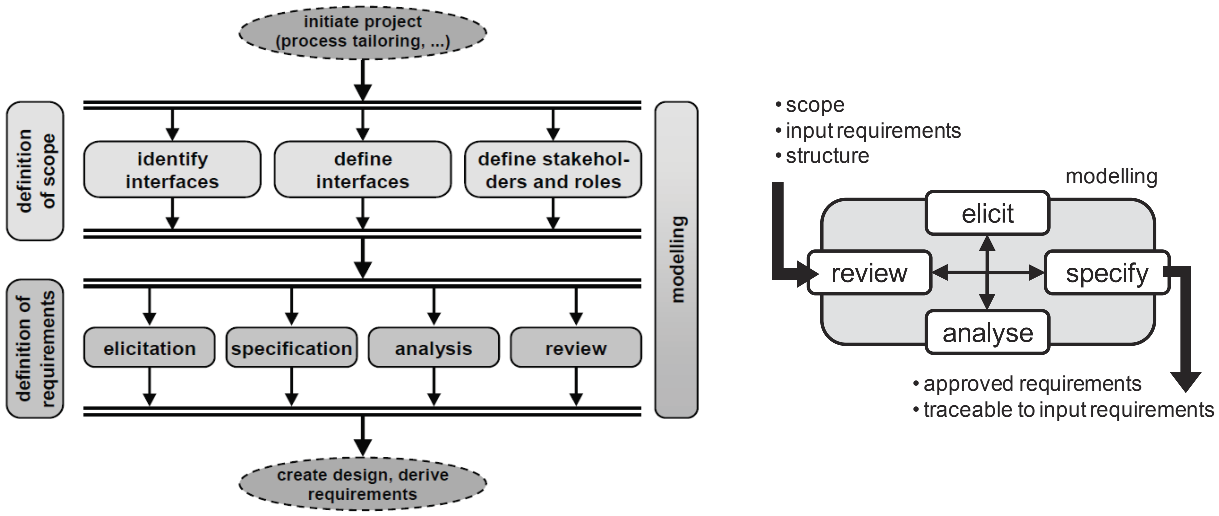

Figure 3-17: Process of requirements engineering[317]

The main support for these tasks is given by a suggested list of suitable methods. Further support, partly based on systems engineering, is focused on requirements *management* in later engineering stages.[318] YU modelled the embedding of requirements engineering activities in the organisation to ensure that developed systems will suit the actual needs of the modelling environment (organisation). He argues that diversity in the early stages in requirements engineering needs to be considered by a specifically tailored modelling framework.[319] AHRENS used factors, such as *consideration of customer requirements*, *transformation into echnical requirements*, *consideration of competition* or *concretisation* as indicators to evaluate the quality of requirements engineering approaches for product engineering. Building on the findings, she developed an approach to elicit and handle requirements with a focus on generating optimal products for the market. The approach includes a procedural model, defining methodological support for each step. It can be specified for different types of projects (e.g. technology push vs. pull), but does not include specific support for modelling links between constraints, objectives and activities. Most requirements engineering approaches focus on handling *existing* requirements, such as strategies to match them to respective product elements.[320]

BERKOVICH et al. propose a new view on requirements engineering by modelling sets of similar requirements as artefacts. By using an artefact model, they propose classification and collocation of artefacts by specifying their relationships. The model is flexible. Changes in state or content of artefacts can be identified by relationships.

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317 Hood et al. 2008, pp.50
318 see also Pohl 2008 for an extensive overview on requirements engineering methods and tools
319 cp. to Yu 1997
320 see, for example, Kläger 1993, Jung 2006, Mayer-Bachmann 2007

A process model shall ensure the provision of activities to enable its integration into the engineering process. Support is provided by a set of methods. This model shall ensure a holistic, interdisciplinary view on requirements engineering. The consideration of constraints has not been explicitly described.[321]

The work of REBENTISCH originates from space engineering and focuses on defining and building a socio-technical system, which not only supports the development of challenging technical architecture, but also ensures sustainability by delivery of value to stakeholders of the eventual product. This includes discussion on stakeholders, their needs and objectives and the objectives influencing the resulting design of the technical system. This research describes existing tools and processes and the development of new tools and processes. Process models are generically built using the Object Process Methodology, allowing a consistent modelling of values and objectives in the process. The approach is in its early stages of development.[322]

MAIER and FADEL have developed a relational theory for design based on the concept of affordances. It lays special focus on explaining relationships between engineers, users and artefacts. They propose an affordance based design model, describing the detection of affordances in contrast to the identification of (customer) requirements. The model is fairly abstract, proposing as its first step the detection of affordances an artefact should have *and* explicitly not have for different users (Figure 3-18). On this basis affordances can be prioritised and structured. They propose a generic affordance structure template to be used in the process.[323]

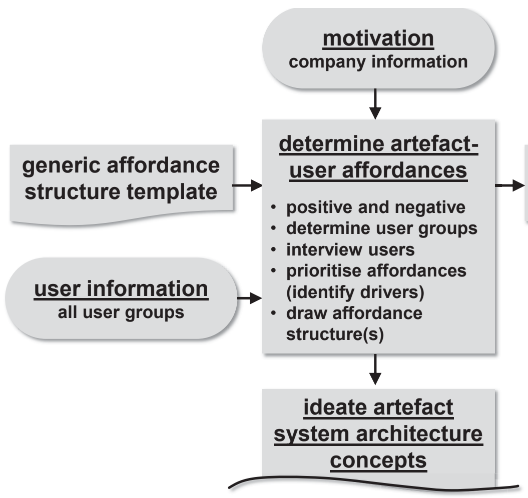

Figure 3-18: Affordance-based design – determination of artefacts[324]

[321] cp. to Berkovich et al. 2010
[322] cp. to Rebentisch et al. 2005
[323] cp. to Maier & Fadel 2006, Maier & Fadel 2009
[324] Maier & Fadel 2006, p. 9

Assessing specific product engineering approaches which deal with the generation of objectives in the light of the requirements identified in section 3.2.1.4 and 3.2.2.4, it can be stated that nearly all approaches are not part of a superior modelling framework. Since most of them suggest a sequential conduction of activities, they do not allow flexible and situation specific modelling for differing purposes, e.g. planning and monitoring the generation of objectives. Additionally, most do not account for a systematic and flexible consideration of constraints and rather focus on handling objectives (requirements) in later engineering stages. These approaches do not deliver support in providing a concept to model objectives, constraints and relationships and their interface to their generating activities. This impedes the active control of the generation of objectives and a sufficient consideration of constraints.

3.2.3.2 Holistic Approaches

Since a holistic modelling framework was identified as requirement for an approach, this section reviews selected holistic approaches from product engineering regarding their suitability to model the generation of objectives and consideration of constraints.

The three-cycle model of Gausemeier focuses on depicting the cyclic behaviour of product engineering processes, highlighting the parallelism of activities and high number of iterations throughout the engineering process.[325]

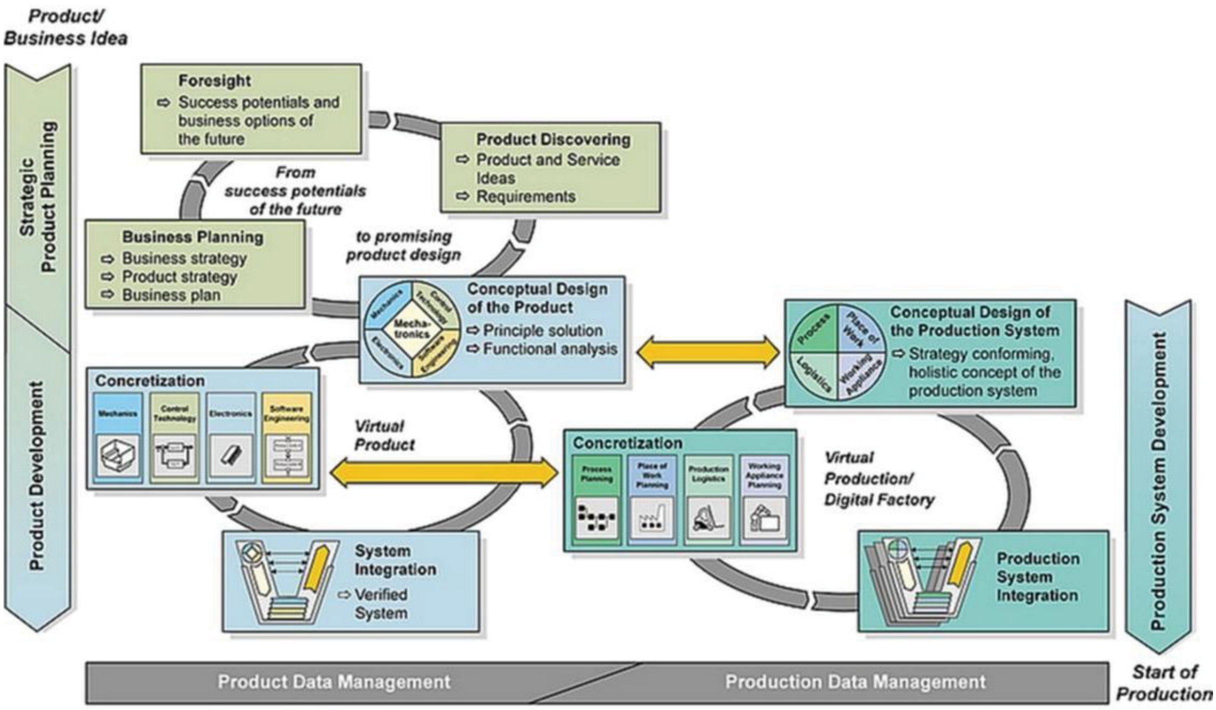

Figure 3-19: The three-cycle model[326]

[325] see also, for example, Langer 2009

The process is abstractly depicted in three cycles: *strategic product planning*, *product development* and *production system development* and their main activities. Interfaces between cycles are outlined. Figure 3-19 shows an overview of main activities, whereas specific contents are described domain-specifically detached from the main model.[327] The model is useful to depict strategic planning procedures in early stages.

HALES and GOOCH present a project focused, procedural approach to capture the engineering process (Figure 3-20).[328]

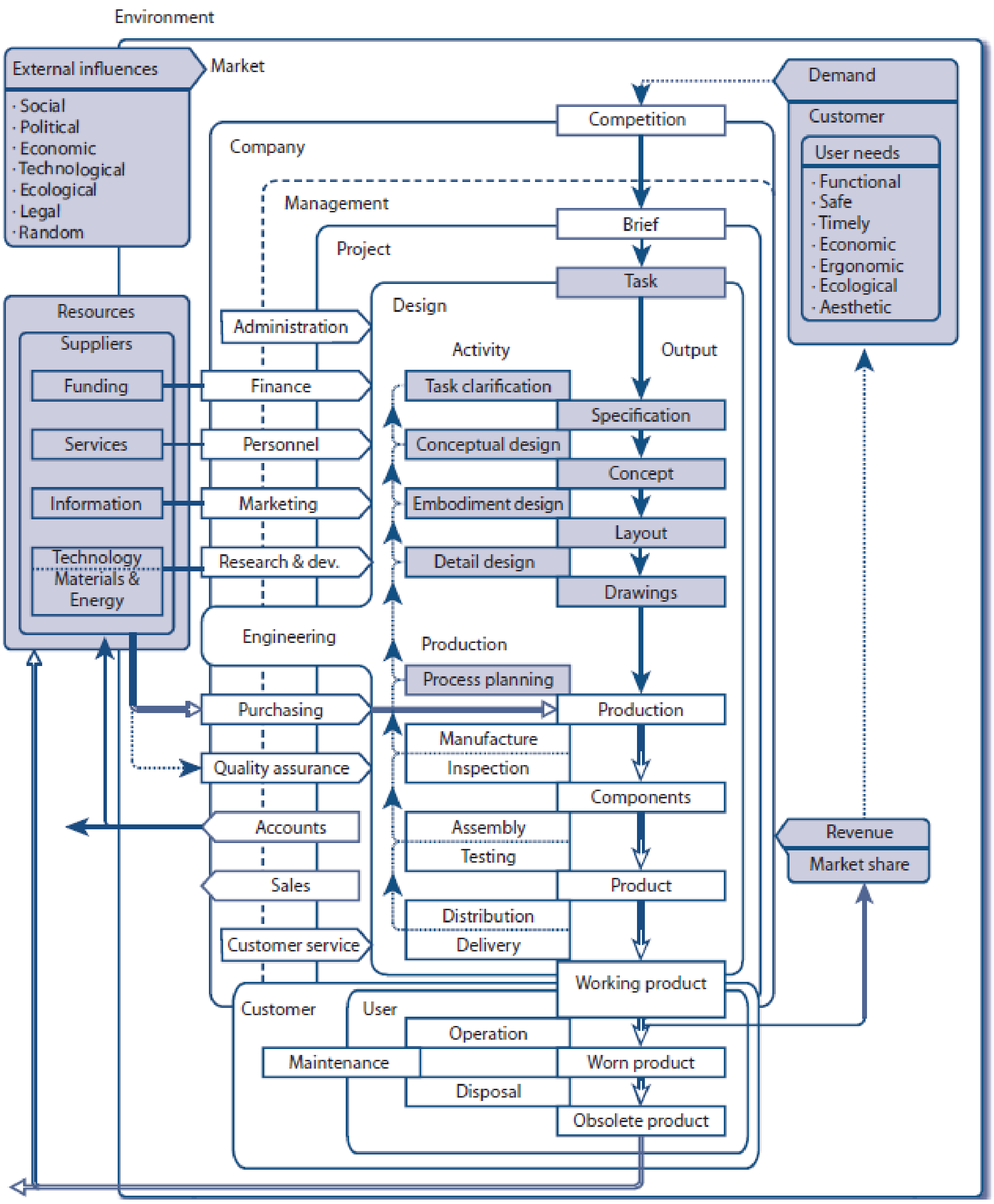

Figure 3-20: Engineering design process in project context[329]

326 Langer 2009, p. 540 (translation), based on Gausemeier et al. 2006, p. 33

327 cp. to Gausemeier et al. 2001, pp. 215, see also Gausemeier et al. 2009

328 cp. to Hales & Gooch 2004, see also section on constraints (section 3.1.3.2)

This approach aims to depict dynamic influences on an engineering project, which are responsible for the uniqueness of each project, by placing the engineering project in its superior context of company, market and environment. Besides project specific influences, it covers project independent influencing factors, not directly manageable or responsive to external influence, such as government legislation. The model is built in different layers, ranging from a macro economic perspective to the specific design project. Activities on each layer are depicted as stage based and influences are explicitly designated. The purpose of this model is to enable analysis regarding influences and their impacts on specific projects, to support process planning by making better informed decisions and to enable continuous improvement.

The ZOPH-Model has been developed as a generically applicable mental aid for the structured analysis, modelling and treatment of complex tasks. As a generic approach, its application is independent from the specific problem. The systemic basis of this model is the findings of PATZAK (section 3.2.1). NEGELE extended this approach to model the system of product engineering (Figure 3-21). The approach depicts the *system environment, system of objectives (goal system), system of objects (product system)*, *process* and *operation system (agent system)* and relationships between these systems. The model comprises different dimensions, where the *generic dimension* consists of three modelling levels. The *generic level* acts as a reference model, containing formal modelling components and syntax.

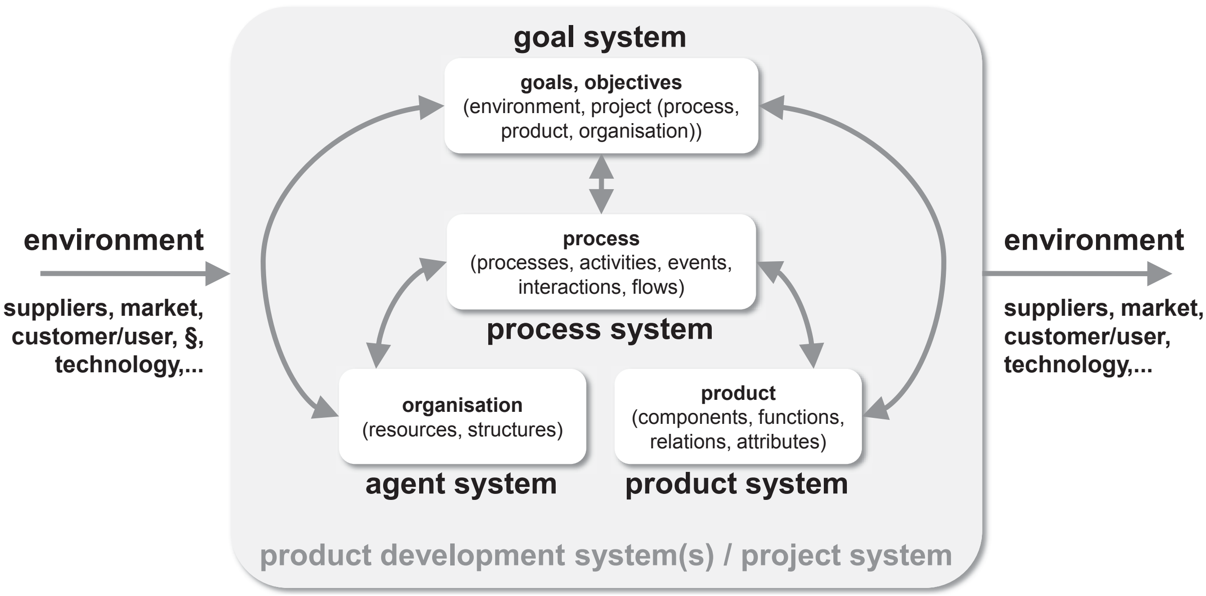

Figure 3-21: The ZOPH-Model for Product Engineering[330]

[329] Hales & Gooch 2004, p. 28
[330] Browning et al. 2006, p. 107

The *partial level* adapts the model to a specific type of problem and generates an appropriate structure. On the *individual level* modelling components are adapted to the specific constraints of a concrete problem. The *dimension of system types* contains the four types of systems. The *dimension of model phases* depicts phases of systemic modelling procedures (analysis, concept, realisation, use). For each phase, contents of all systems are elaborated. [331] The purpose of the ZOPH-Model lies in the analysis and identification of relationships and it is suitable for process planning, continuous improvement, knowledge management and visualisation.

The integrated product engineering model (iPeM), as presented by ALBERS, was developed to describe any product engineering process from an abstract meta model to a specific application. The basic framework comprises a systemic approach to the representation of systems in product engineering as proposed by ROPOHL (section 3.2.1.3). The meta model (Figure 3-22) shows the operation system, system of objectives and system of objects.

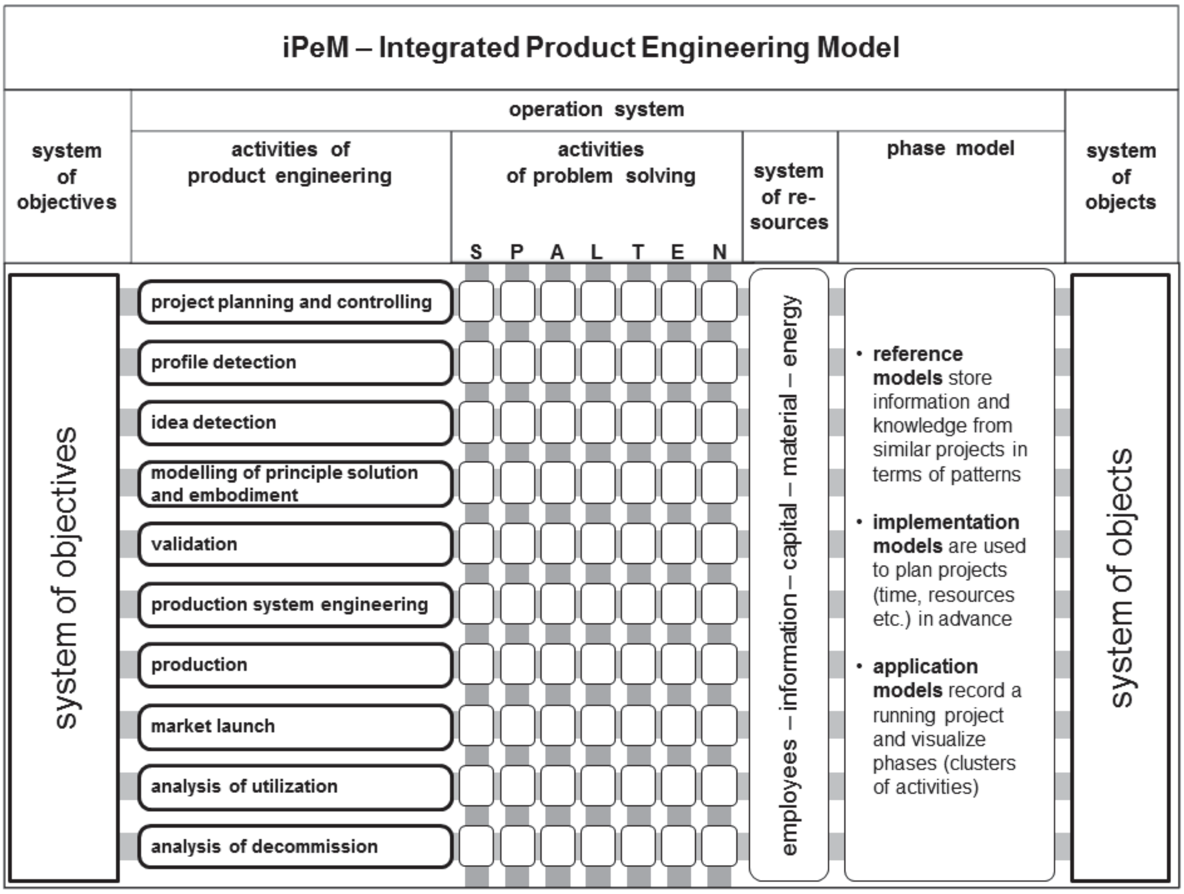

Figure 3-22: The Integrated Product Engineering Model (iPeM)[332]

[331] cp. to Negele 1998, pp. 53
[332] Albers & Braun 2011, p. 7

The main elements of the operation system are activities. They are presented in combination with a stage-based and activity-based approach. The product life cycle is described by the activities of product engineering. The activities of the problem solving cycle (SPALTEN) transform objectives into objects. Together they define a matrix of activities. Activities do not have fixed start or end points. The sequence in which they occur in the actual process is dependent on the specific project. They run in parallel or iteratively. The iPeM model aims to develop a design-oriented depiction of product engineering activities and a project-oriented view for deriving specific process models. Thus, it uses different model levels for abstracting on the formal description of processes. The meta model contains the main building elements for the derivation of more specific reference models, which in turn describe patterns of processes. They constitute the basis of implementation models for specific projects. Application models monitor the actual course of the process in order to derive information about improvement potential for reference models.[333] Hence, the iPeM model can be understood as a generic modelling framework, covering the purposes of planning, executing, controlling and visualising processes. It shall serve for supporting the continuous improvement of processes and knowledge management throughout the engineering process.[334]

The approaches presented are subsequently discussed concerning their ability to fulfil the requirements identified for a suitable modelling approach.

One focus of the GAUSEMEIER's three cycle model and associated methods is strategic planning in early product engineering. Dynamic changes can be addressed by modelling iterations. The specification of external influences on cycles and respective activities is not explicitly described. The generation of objectives is only contained implicitly in the depiction of cycles and is not directly addressable. Interdependences between subactivities and iterations are not considered sufficiently. The use of the model for planning, execution and control purposes is therefore not directly possible.

HALES and GOOCH focus on the articulation of internal and external influences on projects. They account for dynamics in engineering processes by incorporating project specific and project independent influences. The treatment of objectives is only implicitly included in the description of sequential activities. The approach is suited for the analysis of influences rather than for planning, execution and control of activities. Thus it is not appropriate as a holistic modelling framework.

[333] see section 7 for detailed information

[334] cp. to Albers 2010, Meboldt 2008, Albers et al. 2010b, Albers & Meboldt 2007

As with HALES, influences on the system of product engineering can be directly modelled within the ZOPH model. The system of objectives and its interface to the operation system is explicitly shown. Unlike the other models, the approach is generic and adaptable to different levels of abstraction and different perspectives. The main purpose of the model is the analysis of processes to identify relationships between systems and to clearly show interdependencies. Deficiencies in the approach to handle complexity arise because it attempts to be able to fully describe complex systems.[335] A problem specific handling of activities in the operation system and analysis of the impact of changes on the system of objectives is not sufficiently possible.

IPeM represents a modelling framework which can be applied to specific situations, accounting for the dynamics in engineering processes by providing basic modelling elements in its meta model. In contrast to NEGELE, iPeM ensures a problem specific formulation of activities by providing product engineering as well as problem solving activities. It aims to support process planning, execution, control and project development. The system of objectives and its interface to the operation system are included in the model description. However, the description of the system of objectives and the operation system needs to be enhanced to explicitly describe the generation of objectives, assigned constraints and their interface to activities.

3.2.3.3 Implications

This section discussed selected specific and holistic product engineering approaches with regard to their suitability to improve the process of generating objectives on the basis of constraints. Besides the fulfilment of the previously identified requirements, this requires the ability to model constraints, objectives, activities and relationships on a generic and systemic basis. What is clear from the discussion is that both specific and holistic approaches focus more on the later engineering states where there is less uncertainty, and in which objectives are principally known and (only) need to be handled. Apart from suggestions for the use of specific methods, there is no consistent approach that is actually able to model the coherence of constraints and objectives in a specific situation throughout the *generation* of objectives and other associated activities, which are conducted and need to be planned and managed throughout the generation process.

[335] cp. to Pulm 2004, p. 94

3.2.4 Implications

This second part of the discussion of current literature aimed at identifying means with which the generation of objectives, and a sufficient consideration of constraints, can be modelled and improved on a systemic basis.

Systems thinking has been discussed regarding its utility as a mental model to be used as the basic means for a potential improvement approach. It was shown that existing theoretic reflections provide a profound basis to depict objectives in their systems engineering environment. Based on these insights, requirements to be considered from a systemic perspective were derived.

The requirements resulting from the required applicability of the improvement approach in a product engineering context formed the basis for discussing specific and holistic approaches from relevant research areas regarding their suitability to meet these requirements. It was found that none of the studied approaches provided by current literature are able to sufficiently support the generation of objectives consistently and flexibly in the early product engineering stages, which are characterised by a high level of uncertainty. Since iPeM provides the most extensive modelling framework with regard to the defined requirements, it was chosen as the basic modelling framework to support the research described in this thesis.

4 Aim of Research

The aim and contribution of this thesis are derived from the previous investigation of the state of the art in literature. This investigation discussed literature related to the initial problem specification:

- Which problems occur during the generation of technical objectives and their alignment to relevant constraints?
- How can such problems be overcome, i.e. valid technical objectives be generated whilst maintaining alignment to relevant constraints?

Regarding the first question, empirical insights from research on early engineering stages, of particular importance to the generation of objectives, have shown that these are still perceived as intangible. Reasons are high uncertainty due to dynamic project constraints and the early development state, as well as little standardisation and formalisation of processes, methods and tools. Responsibilities and contributing people are often not obvious. A review of relevant modelling approaches further showed that there are no approaches which consistently describe activities relevant to the generation of objectives. These insights motivate the first research hypothesis:

Research Hypothesis 1

Technical objectives are generated by activities which are carried out mainly implicitly by different individuals with little central regulation. This impedes an active and efficient support of this process.

The peculiarities of the early stages are assumed to influence the outcome of this stage, but the actual influence of these peculiarities on the generation of objectives has not yet been studied. Dynamically changing constraints to engineering projects, such as environmental trends or the development of competition, are discussed and classified. Though emphasising the relevance of these constraints for projects, there are no *holistic* approaches to ensure they are considered in the formulation of objectives. Even though uncertainty has been identified as the main factor influencing the outcome of these early stages, approaches to uncertainty do not establish a proper link to the relevance of this issue for future-oriented constraints and the generation of technical objectives. Much research has been spent on the role of objectives in problem solving processes in engineering. In particular, their relevance to deriving criteria for decisions has led to the specification of multiple requirements on the formulation of objectives.

Despite the importance of the fulfilment of these requirements for the outcome of decisions, potential uncertainty in information and knowledge used for deriving objectives has not been investigated as influencing factor. Decisions are made subjectively and depend on the perceived uncertainty of the decision maker. Although decisions themselves are necessary to generate and fix objectives, the relevance of the subjectivity and uncertainty of the individual has not been linked to the quality of resulting objectives. Together, the different research areas highlight factors which seem to have relevance for understanding why the generation of objectives and their alignment to constraints does not always run smoothly, but the actual link to objectives and the impact on their generation has not been researched.

Research Hypothesis 2

The development of objectives and the way and extent to which constraints are considered depends on various influencing factors and their interdependencies.

The second hypothesis in turn provides the basis for the formulation of the third hypothesis. It is assumed that if there are factors which negatively influence the generation of objectives, an active manipulation of these factors must provide the possibility to improve their generation.

Research Hypothesis 3

The improved development of improved objectives can be achieved by actively manipulating the influencing factors.

The discussion of systems thinking as a means to support the generation of objectives and related constraints has shown that existing approaches have developed ways to represent objectives and to model their embedding in engineering processes. The analysis of existing specific and holistic engineering approaches revealed a demand for a more sophisticated approach to depict the generation of objectives on the basis of a generic modelling framework. The comparison of the approaches with identified requirements for a systemic approach in an engineering environment supported the selection of iPeM as the basic modelling framework for subsequent research.

Research Hypothesis 4

The development of objectives can be made explicit by using the systemic modelling framework of iPeM, making the process more accessible to active improvement and management.

By analysing the current state of the art and deriving basic research hypotheses, the key problem statements identified earlier could be tailored to the existing research demand. Thus, the overall research aim can be formulated as follows:

Research Aim

- Identification of factors which inhibit the generation of objectives on the basis of relevant exogenous and endogenous constraints.
- Development of an approach based on iPeM to make the generation of objectives accessible to operative management and improvement.

This aim is to be achieved by elaborating answers to the resultant research questions in the subsequent chapters of this thesis:

Research Question 1 (→ Chapter 5)

How are technical product objectives generated, how are constraints from market, product environment and company considered and which factors influence this process?

Research Questions 2 & 3 (→ Chapter 6)

Which factors influence the development of objectives and in what way?

Which of the factors can be influenced and in what way?

Research Question 4 (→ Chapter 7)

How can the development of systems of objectives be made explicit and thus manageable and improvable for operative use within the modelling framework of iPeM?

Considering the insights described in the preceding chapter, the approach to be developed needs to cover the following requirements:

- establish a theoretic basis to understand and handle systems of objectives, whilst ensuring applicability in practice with focus on early development stages
- support systemisation, standardisation and transparency and also allow flexible adaptation of approach due to changing environmental and design situations
- increase efficiency of the activities undertaken and improve their outcome
- provide a basis for further research in this new research area.

To ensure the practical relevance of this research focus, the elaboration of the approach of this thesis starts with an empirical investigation of the identified research issue in the context of the automotive industry. On the basis of these findings, relevant theory and an improvement approach are developed and subsequently verified in the practical environment of the empirical case study.

5 The Empirical Case

This section studies the practical relevance of the previously defined problem and research scope with a focus on the first research question. This is essential to ensure that the solution approach to be developed in this thesis is applicable to the demands of industrial practice. The results of empirical studies conducted at the automotive manufacturer Dr.-Ing. h.c. F. Porsche AG are presented. These studies focused on finding out how technical product objectives are in fact generated in practice and how constraints from the product´s environment, market and company are considered within this process. Furthermore, weaknesses of current processes and potential reasons for their existence are identified. This section argues that the processes that generate technical product objectives are mainly implicit and executed in a decentralised manner by a variety of contributing individuals. A systematic integration of constraints is not explicitly defined. These processes are also impeded by various different influencing factors. Due to these reasons, a holistic, active and efficient support of the respective processes is needed, but does currently not exist.

5.1 Overview

The empirical investigation was carried out in a three year research collaboration between the IPEK (Institute of Product Engineering) and the car manufacturer Dr.-Ing. h.c. F. Porsche AG, conducted by the author of this thesis. Even though results of the study are limited to one company, the intensity and depth of the investigation offer substantial insights into the current capability of a company in handling product objectives in the early engineering stages of product development.[336]

5.1.1 Company Background

The Dr.-Ing. h.c. F. Porsche AG[337] is a German automotive manufacturer founded in 1931 in Stuttgart by Ferdinand Porsche. The company's headquarters is located in Stuttgart Zuffenhausen and the development centre is in Weissach (both locations are in Germany). Main production sites are in Zuffenhausen and Leipzig, Germany. Porsche AG currently employs around 12,700 people, with around 4000 in the development centre in Weissach. Following the global recession, Porsche AG raised its turnover to 7.7 Billion Euro in the financial year 2009/2010 by selling 81,850 cars.

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[336] see section 2.1 for methodological procedure during empirical research, see also section 1.1.3
[337] subsequently referred to as Porsche AG

The early days of the design office in the 1930s were marked by developments for different customers, the most famous being the construction of the VW Beetle in 1934, thus laying the foundation for the subsequently founded Volkswagen GmbH (today Volkswagen AG). After the Second World War, Ferry Porsche, son of the founder, promoted the development and production of the first series vehicles named *Porsche*. The most famous representative, the Porsche 911, was launched in 1963, as second product line to the Porsche 356, the initial model. Today, Porsche AG develops and produces four car series, serving *sports* (911 Carrera, Boxster/ Cayman), *limousine* (Panamera) and *SUV* (Cayenne) car segments (Figure 5-1).[338]

Figure 5-1: Product range of Porsche AG[339]

5.1.2 Business Context and Practical Research Objective

The automotive industry has a particular challenge to reduce development times, while demands on quality and innovations rise, since the final profitability of new concepts highly depends on satisfying various exogenous and endogenous constraints.[340]

Current efforts at Porsche AG attempt to consider such constraints as early as possible in the definition of their car concepts. The idea is to gather information about trends, technology, market and competitors to be able to predict their development and the future competitive environment. Objectives of their concepts are derived on this basis to position them relative to the competition. In such early project stages market launch is still far off in the future. Problems are encountered in systematically reducing uncertainty while describing a future state of the market, competition etc. as well as for describing their own feasibilities and objectives. Past projects revealed (in later development stages) that this affects the validity and consistency of the entire objectives of the product.

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338 cp. to Porsche Automobil Holding SE 2010, Orel 2009, Cotton 1988, von Frankenberg 1969
339 Dr.-Ing. h.c. F. Porsche AG
340 see Introduction, section 1.1

Activities are carried out by many engineers, but are perceived to be conducted rather in isolation, lacking methodological as well as tool support. Thus, a short term assessment of questions related to objectives and efficient collaboration is often not easily possible.

Due to this situation, senior management decided to concentrate efforts on improving the generation of technical objectives in the early stages by finding solutions to these issues. The main goals of these efforts were the improvement of the:

- *validity*, *consistency* and *comparability* of objectives;
- *transparency* (explicitness) of the *system* of objectives (constraints, objectives);
- *efficiency* and *flexibility* in generating (the system of) objectives.

The research collaboration, initiated as part of these efforts, focused on studying the issues for activities related with transferring environment constraints (development of trends, technology and competitor) into the definition of objectives.

Aim of Research Collaboration

Develop an approach to improve the definition of product concepts in early stages of product engineering by supporting a transparent, valid and consistent provision of environmental, technological and competitor constraints as a basis for the generation of technical product objectives.

5.2 Processes, Methods and Tools

The first part of the empirical study aimed to achieve a deeper understanding of how objectives are generated in practice during the early stages of product engineering. Findings showed that exogenous constraints, such as relevant competition, were regarded as essential aspects to be considered in the derivation of a product's objectives. However, there were problems in integrating such information, when provided by the department responsible for them, into the actual objectives. A closer look at the key activities showed problems, such as an insufficient consideration of uncertainties and a lack of knowledge about dependencies between the constraints and objectives. The activities are currently supported by methods and tools inappropriate for requirements of uncertain and dynamic early engineering stages.

5.2.1 Findings

5.2.1.1 Objective Development in the Vehicle Development Process

The development process is structured in stages according to a stage gate model. The main stages are divided into *early stages*, *concept development*, *series development* and the preparation for *production*, and are linked by defined milestones (Figure 5-3).

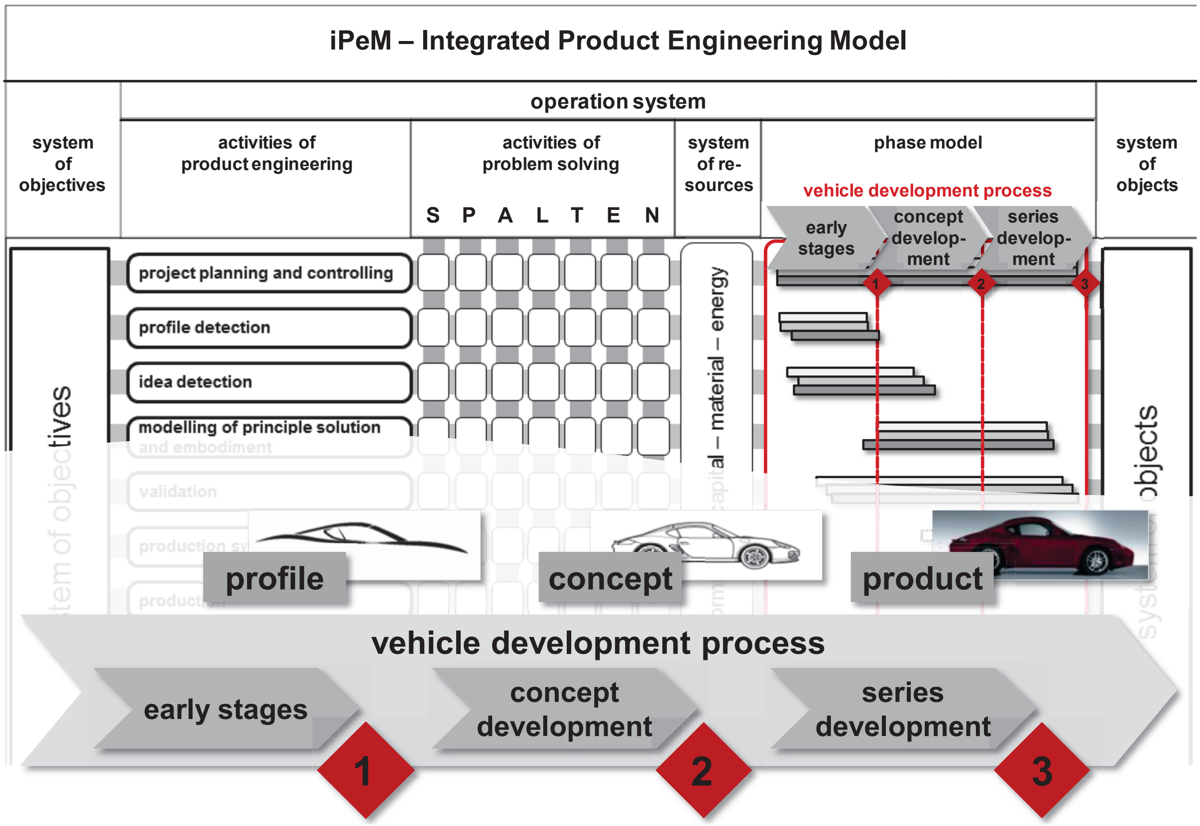

Figure 5-2: Main stages of the vehicle development process[341]

The early stages cover all the activities performed before the official start of a development project and serve to derive a first product specification (1). This specification is further detailed during the concept development stage. The result is a fully specified car concept and first embodiments of the concept in form of prototypes (2). Series development activities concretise the concept into the final product and provide the basis for subsequent production (3). Figure 5-2 further shows an image of the main stages of the vehicle development process in iPeM.[342] This visualisation shows that stages in this context are understood as clusters of activities, whereas their exact sequence and duration depends on prevailing project constraints. Thus they cannot be depicted as being strictly sequential. This differs to the understanding of many conventional approaches from design literature (e.g. VDI2221).[343]

The development of objectives throughout an engineering project is not explicitly described by an official process at Porsche AG. By analysing official documents due at different milestones in a project, including information on the required state of the objectives, four main stages in the development of objectives could be identified.

341 Own illustration, based on internal documents, Dr.-Ing. h.c. F. Porsche AG. The duration of activities in iPeM does not relate to an existing development project.

342 as presented in section 3.2.3.2

343 see VDI 2221 1993

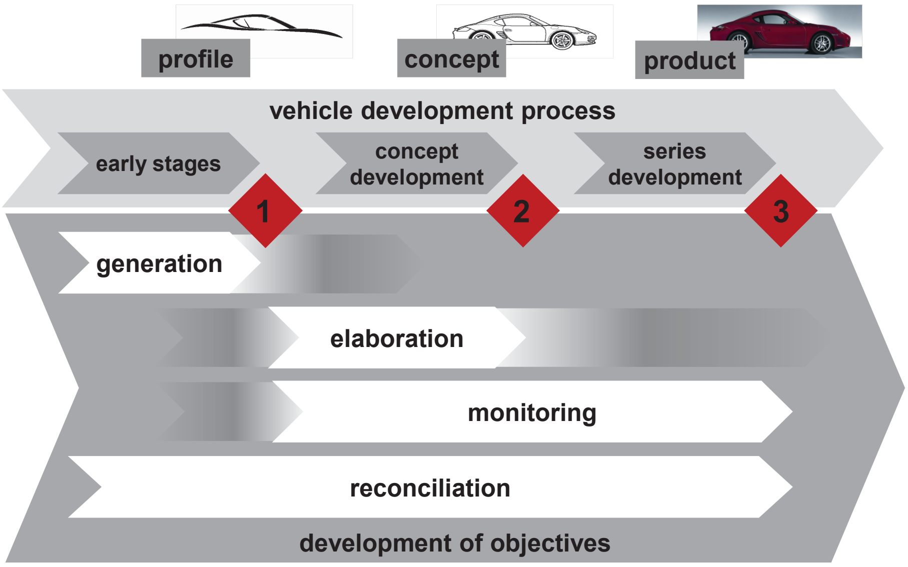

Figure 5-3: Main stages in the development of objectives[344]

Interviews with participants of the process revealed that these stages are not always clearly separable. Activities for the generation of objectives may also be conducted in concept development stages, for example, because important information was not delivered earlier (faded bars, Figure 5-3).

The required result of the early stages of a car development is a first specification of the future product. This specifies the product´s strategic position in its future competitive environment by outlining its main features and characteristics. These include, besides the description of the relevant environment, a profile of main product parameters, such as performance, package, weight and fuel consumption as well as technologies planned to be implemented in the future vehicle. The values of these parameters are objective values, representing anticipated parameter values for the future car. They constitute the framework for all future development activities. The contents of this specification are derived from an analysis and prognosis of the development of the environment of the project, based on the main project constraints, such as financial resources or strategy. Objective values for each included product parameter are derived individually by the relevant functional department. The analysis and prognosis of the environment and the derivation of objective values for product parameters is summarised as the *generation* of objectives (section 5.2.1.2). Reflecting on the content of the early stages at Porsche AG, it becomes evident that they differ from the conventional understanding of early stages which are often associated with concept development activities.[345]

[344] own illustration, based on internal documents, Dr.-Ing. h.c. F. Porsche AG
[345] e.g. VDI 2221 1993, Pahl & Beitz 1995

During concept development at Porsche AG, initial objectives are substantiated by elaborating specific constructive measures on how these objectives can be achieved. In some cases, adaptations of initial objective values are made. Objective values are broken down to unit and component level by the relevant functional department and these values are determined as soon as details about the product structure are known. For example, the objective value for a vehicle´s weight (e.g. m = 2000 kg) is decomposed down to the weight of each component (e.g. $m_{\text{brake disc}}$ = 10 kg). These objective values must be met by the relevant department when working on a specific component. Further revisions of objective values are made when a detailed parts list is available. Upon completion of concept development, the entire set of objectives must be free of conflicts. Unresolved inconsistencies or unforeseen constraints may cause an adaptation of objectives values in series development. These activities are known as the *elaboration* of objectives.

After the formulation of objective values in the first product specification, objectives values are used as nominal values to measure the actual development state and account for deviations to the as-is values of product parameters. This comparison is particularly used for important product decisions. If deviations of the as-is to the should-be state cannot be solved by adapting the design or technologies, or if important constraints change, objective values are sometimes agreed to be changed. This might make recalculations of interrelated objectives necessary to keep consistency between objectives. These activities are known as *monitoring*.

Throughout the development process objectives need to be reconciled. This includes constant discourse within and between departments responsible for a specific objective to agree on the validity, consistency and comparability of a specific objective or the entire set of objectives. These activities are known as *reconciliation*.

By analysing different projects, it was found that there was no fixed sequence of the different stages in the development of objectives. Their allocation to specific stages in the vehicle development process was not possible, since no fixed beginning and end of such activities could be defined (cp. to Figure 5-3). Their execution seemed instead to be dependent on the specific constraints of each development project.

5.2.1.2 Generation of Objectives

After the analysis of the overall development of objectives in respect to the vehicle development process of Porsche AG, the empirical investigation focused on finding out how objectives are in fact generated in the early stages. Again, no official description of the activities contributing to the generation of objectives could be found. After analysing several projects, three main, recurring clusters of activities concerned with generating objectives could be identified (Figure 5-4).

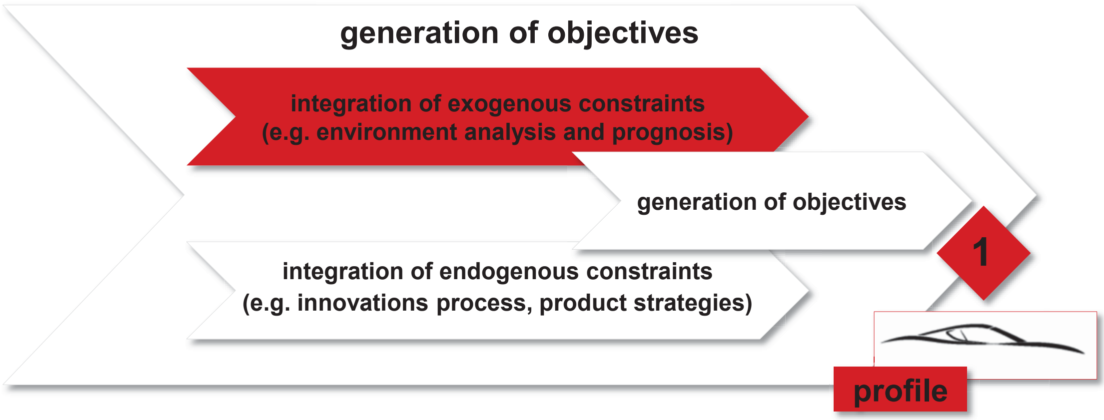

Figure 5-4: Main activities during the generation of objectives

The first cluster contains activities for analysing and predicting the development of exogenous constraints. This includes efforts by the sales department to detect relevant customer requirements, a constant monitoring of legal institutions for changing regulations, law and patents as well as analysis and prognosis of the environment (trends, technologic developments and changes in competition).

The second cluster comprises activities related to the development of product strategies and the regulation, management (innovation process) and development of new technologies. Both clusters of activities cannot be assigned to a distinct stage in the development process, since they are partly executed independently from a specific project (e.g. innovation process, strategy).

The third cluster includes activities concerned with the actual derivation of objectives. Departments responsible for the derivation of a certain objective parameter start their activities at a non-official point in time, after the first impetus for the project when the date for the finalisation of the first product specification is scheduled. Values for established objective parameters are derived by the department which is responsible for the product parameter and its engineering environment (e.g. c_d – value/drag by department for aerodynamics). Evaluating the different statements of the interviewees from different departments, no generalised procedure is used for deriving an objective. Several engineers reported that they reconcile internally set constraints with exogenous constraints to ensure a proper positioning of the product in its future market. The extent to which exogenous constraints were in fact used in the definition of an objective seemed to differ between different departments. Also the procedure to balance endogenous and exogenous constraints remained unclear. Interviewees reported that a sufficient integration of exogenous constraints is impeded because results from the environment analysis and prognosis do not provide explicit guidance on what they mean for their own product objective and how they need to be considered. A lack of transparency on how the results were derived further aggravates this consideration of objectives.

Endogenous constraints (e.g. strategy) are regarded as mainly fixed in their influence on objectives. Exogenous constraints, especially the development of the environment, are perceived as crucially important for setting the “right” objective.

5.2.1.3 Environment Analysis and Prognosis

Since activities concerned with the environmental analysis and prognosis (marked in red, Figure 5-4) had been identified as crucial, but a bottleneck to the generation of objectives, these activities were reviewed in detail. Responsible employees and customers of the results (cp. to previous section) were interviewed and documents were viewed regarding the procedures, methods and tools used.

Activities for analysing and predicting the environment are performed by one single department. In a similar way to the previously described activitiy clusters for the generation of objectives, the activities to analyse and predict the environment are not officially defined with regard to content, duration, responsibilities and sequence. Further research using interviews and documents of each department showed that there was also no process description existing at the department level. Activities performed by the department were detached from specific projects in the company. Twice a year, the department produced a summary report of relevant developments in the environment, containing information for all different production series within the company. Customers of this report criticised that results are often not up-to date in regard to a specific vehicle project, since the different projects addressed always run at different maturity levels and require different types of information.

From observing activities, methods and tools in the department and by analysing previous reports, an overview of the key activities was derived, showing all identified, regularly performed activities. There are three main subjects that are worked on, which are relevant as the main contribution of the department to the generation of objectives. Interestingly, on an abstracted level, the same basic activities can be used to describe the elaboration of each subject (Figure 5-5).

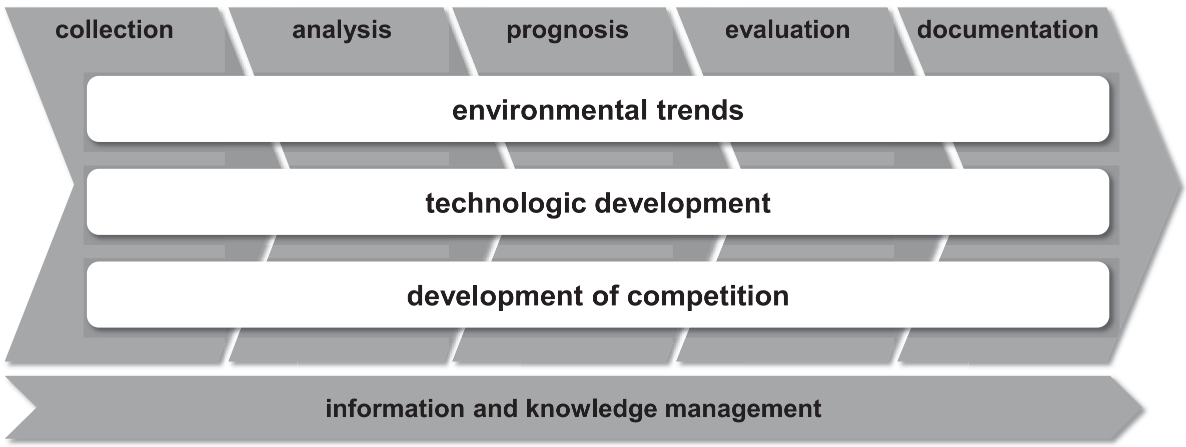

Figure 5-5: Activities during the analysis and prognosis of the environment

The *environment* of Porsche AG is constantly monitored. Publicly available sources, such as publications in the internet or press, studies by renowned institutions, exhibitions or personal contacts are continuously reviewed to track new information or changes in existing information which could be relevant for new product developments. This information is analysed regarding its quality and relevance. Past trends are identified and used to predict a future development in these trends. This can be a trend towards rising awareness of customers to environmental issues or rising sales numbers for cars with diesel engines. This prediction is usually based on a forward projection of past trends. The time horizon looked at in this projection is 10 to 20 years in most cases. The main trends and further relevant information are extracted and classified with regard to their relevance for a specific production series within the company. The results are included in the departmental report.

Besides analysis and identification of trends, collected information is used for tracking the *development of technologies*. This implies particularly analysis of publications by scientific research institutions, such as universities, research activities of suppliers and the competition. The aim is to formulate a roadmap on when new technologies enter the market and which improvement potential they provide for the use in future cars. Depending on disposable information, technologies in the roadmap are based on directly transferred published information or on their own anticipation of technologic trends. This anticipation is based mainly on prior knowledge on research activities of relevant key players and trends. The resulting technology portfolio is provided in the overall report of the department. Moreover, it is used for predicting future development of other competitive organisations.

The focus of the environment analysis and prognosis of the department is set on the prediction of the future *development* of relevant *competition*. The department employs specialists, knowledgeable about the philosophy, strategy, past development and current range of products of a specific competitor company. In addition to the information elicited regarding environmental trends and technologic development, they collect information specifically relevant to the associated company regarding potential changes in strategy, range of products and most importantly new future products. Based on this information, and in reconciliation with the sales resort, core competitors for each own product series are identified. By using this information pool and prior knowledge of a core competitors strategy, the future development of the product range is anticipated to detect future car models representing direct competition to their own product. After setting the frame for determining the development of the product range, which includes the definition of potential future motorisation variants, the key product parameters for relevant future competitor cars are predicted. These parameters correspond to main product parameters in the first product specification of the own product to enable comparability to own objectives.

Firstly, parameters regarding the car concept are derived, such as package measures, weight and aerodynamic parameters. Secondly, dependent parameters, such as driving performance values and fuel consumption are calculated. These calculations are based on algorithms derived from statistical evaluations of parameter dependencies. The results of the core competitor analysis for their production series are summarised and overviews describing predicted parameters in diagrams are generated to aid visualisation of the anticipated state of competition at point in time when the new products enter the market. Results are included in the overall report.

5.2.2 Analysis and Interpretation

Results of the investigations were analysed and evaluated to identify shortcomings in activities of the environment analysis and prognosis and in the transformation of their results into the generation of technical objectives. Based on the initial aim of senior management to be achieved within this research project, the activities, methods and tools were analysed regarding their validity, comparability and consistency of results produced and issues impeding an efficient and flexible process execution.

5.2.2.1 Process

Regarding their *embedding in the superior process*, the results from the environment analysis and prognosis are regarded to be crucial for deriving values for objective parameters. Consequently, information which is up-to-date and tailored to constraints of each specific project is needed. Since the results from these activities are only provided twice a year, and not synchronised to specific project timetables and not customised to current questions raised in the specific projects and provided in an extensive, unhelpful format, their smooth integration and consideration for positioning objectives is not possible without additional redundant effort. During the elaboration of the report, internal customers are involved only late on for reconciling intermediate results or for integrating additional information. Results are, in most cases, only published when they are finalised, leaving no room for discussions and thus lowering the acceptance of the results to be considered with regard to the objectives.

Concerning the *modelling and management* of *activities*, there are no existing process models depicting activities and enabling planning, regulation and improvement of processes and their efficiency. Durations for the activities are not set and meetings for reconciliations are not fixed. Predecessors and successors of activities are not defined. Responsibilities for the activities are not always clearly set. Additional orders, not contributing to the main task of the department, interrupt the execution of activities relevant for the main task, leading to delays. These conditions offer little room to plan and manage activities. Changes in process execution which do not lead to loss of schedule are barely possible. Results vary widely in quality due to a lack of opportunity for reconciliation and minimal review.

Regarding the *conduction* of *activities*, steps to be conducted to achieve specific results in the elaboration of the main task, are not defined. Activities are executed mostly individually by each team member. Results are rarely synchronised during the process, only during their finalisation before the publication in the report. This creates redundancies in the elaboration of results and impairs the comparability of results.

5.2.2.2 Methods and Procedures

Compared with equivalent departments in other companies, the team responsible for the environment prognosis and analysis is relatively small and thus not able to use extensive forecasting or competitive intelligence methods or tools. The use of methods and procedures is characterised by a pragmatic application of procedures that have proven to be successful in the past. An analysis of these procedures, evaluation of documents and answers, particularly from the customers of the results revealed several shortcomings. These have arisen due to requirements regarding on the quality of information relating to the future development of environmental constraints because of the importance of this information for their objectives.

Regarding the *handling of uncertainty*, several uncertainties in elaborations could not be reduced and uncovered, even though evaluations of past predictions have shown a relatively high probability of occurrence. These are partly aleatory uncertainties, that are impossible to anticipate, such as a natural catastrophe impacting sales and thus causing a change in their competitors (and maybe their own) strategies relating to the launch of new products. Past documents revealed that other epistemic uncertainties were not mitigated, mainly because no systematic strategy was used. An important aspect in this case is that predictions of developments, no matter if they concern general trends, technologies or future competitor cars, postulate only one future scenario to be possible. The results suggest one distinct point in the future as a focus for the generation of their objectives. This perspective neglects the dynamic behaviour of the exogenous constraints and is not able to cover alternative developments caused by changes in constraints. If, for example, one core competitor decides to invest in performance rather than in fuel reduction technologies and this alternative is not anticipated in the prediction of the environment, the prediction is useless. Sources used for the collection of information are not systematically managed as they are not generally discussed and evaluated concerning their reliability, ignoring the potential uncertainty induced by imperfect information. Sources are used individually and not reconciled within the team. Since the disposal of collected information in repositories happens individually and available information might not be known by other team members, uncertainty due to a lack in information is not systematically accounted for. Redundancies in elicited information result.

Analysing the *consideration of dependencies*, it became obvious that results from the different subject areas considered are partly building on each other. For example, the knowledge about which technologies will be available in five years is necessary to predict which technologies a specific competitor will be able to implement in a new car launched in seven or eight years time. Some dependencies are self evident and are obvious to the respective employee, in part due to their prior knowledge and experience. Other dependencies are not self evident; in particular those which exist only indirectly, such as the impact a new regulation might have on a competitor's strategy. Besides identifying it, the measurability of such an impact is a challenge. Nevertheless, a prediction of quantitative parameters of future competitor cars is not possible if the impact of a fuel saving technology on the fuel consumption of that car cannot be formulated in numbers. The implicitness of such dependencies in early stages impedes their consideration. Procedures of team members revealed that intermediate results of activities are not consistently linked and dependencies are consequently not evaluated. This leads to a story line, which is in the end not consistently argued regarding premises used in each step. This might lead to results which are less valid and not consistent with results from other team members. A comparison of results cannot be sufficiently made due to unknown premises of individuals. Another issue was a lack of overall interpretation of the results for their own development projects. Courses of action in such a project, i.e. consequences for the derivation of their objectives are not derived. This aggravates the use of the results in the generation of their objectives.

The visualisation of dependencies between constraints and objectives becomes complex at some point. An explicit description of dependencies is important to enable evaluation regarding quality and uncertainty as well as reproducability of results by others. The *lack in transparency*, especially in intermediate results aggravates their comparability. Customer focused documentation of the results has not been realised.

The methods used for environment analysis and prediction use a broad information base, both from new publications as also from prior knowledge. The collection and handling of information require time and effort. In particular, the prediction of changes in a competitor's product strategy involves the elicitation of a broad range of current products to find indications of potential changes or to be able to speculate on potential alterations. There is a *lack of flexibility* in integrating changes in observed exogenous constraints into running analyses and predictions, since this leads to an enormous amount of effort required for updating all the associated information. This is difficult because information items are not explicitly linked. Thus the whole information base needs to be checked for a potential update. Besides an insufficient update of the information bases, changes are sometimes even ignored. This may lead to outdated prognoses and even useless results.

Since methods and procedures are highly influenced by individuals, regular reviews to update procedures to new requirements are barely possible and not conducted.

As noticed for the conduction of activities, there are *individual differences* in applying methods or procedures depending on experience and prior knowledge. This impedes comparability and an objective assessment of results, while it potentially increases uncertainty of the results. Information and knowledge from previous processes is not incorporated on a standardised basis. Little reconciliation among team members often results in additional effort and differing results.

5.2.2.3 Tools

The use of tools is not standardised. Interviewees reported to use mainly their own documents and tools, i.e. self-developed, for example, in MS Office. The only common tool was a database, developed in the department to support the handling of information on competitors and technologic developments. Further information is stored individually in local or network repositories. It was stated several times that available tools are not adequate for grown requirements. A modelling of constraints, such as competitor cars, cannot be done with tools for the later stages, such as CAD or calculation models, due to the specific information needed for such models which is not available in the early stages. Process management is mainly done intuitively and without tool support.

The existing database does not provide functionality to account for different states of information to *handle uncertainty*. Thus, a consistent assessment of information concerning its imperfection is not supported. Tools, in particular, the ones created individually are in most cases not linked. Information cannot be transferred without risking imperfection due to mistakes in the transformation.

There is a *lack in* supporting *transparency*, since the tools used do not support the transparent documentation of activities conducted or the deposition of information at distinct points during the elaboration. Furthermore, modifications of information are not visible and reproducible in later assessments.

A *consideration of dependencies* between information regarding different constraints and relationships to objective parameters is not supported. Thus, dependencies cannot be made explicit by available tools. Since there is little reconciliation during the activities, inconsistencies may evolve and the quality of the results may suffer.

The processed information does not always share a common reliability or state. Current systems are not able to handle different types of information provided. Most of the tools have been developed generically, thus they do not build on a systematic underlying functional model and *lack in* their *flexibility* to adapt. New or further requirements on tools cannot be easily integrated within the concept of each tool.

Since there are no regulations regarding the deposition of information, there are *individual differences* when depositing data. Higher effort and redundancies arise, since there is no overview of existence and location of information. Since different individuals use different tools, it is more difficult to synchronise data and ensure comparability. Handling information is especially difficult for new team members.

5.3 Influences on Decision Processes

The initial investigations of the study revealed that a large number of the activities to generate objectives and to predict the development of the environment are conducted implicitly and individually. The eventual outcome of these activities seems to be not only dependent on a "complete" consideration of the "correct" constraints, but also on the use of appropriate methods and tools. Based on this insight, the proposition emerged that when an objective is evaluated concerning its validity, consistency and comparability, it is necessary to account for the circumstances in which the objective was generated. In particular, the way in which *procedures* are conducted by individuals, the available basis of *knowledge* and *information* and the *communication* and *reconciliation* in activities were assumed to influence the resulting objective to a significant extent. Considering the bootstrapping issue of objectives and decision making as identified in literature research, the subsequent hypothesis was derived:

Hypothesis

Decision making processes are influenced by multiple factors. Due to the contingency of objectives and decisions, these factors also influence the generation of objectives and thus the resulting system of objectives.

This hypothesis motivated the conduction of the second round of interviews, including talks with engineers responsible for generating objectives as well as team members doing environment analysis and prognosis. Together with observations made, documentary material and tools (e.g. databases), this specific investigation aimed to substantiate the hypothesis by answering the following research questions:

Research Questions

- How do different procedures, available knowledge and information as well as reconciliation and communication during early engineering activities influence decision making processes?
- Which further factors can be observed to affect decision making?

5.3.1 Findings

This section describes insights from the second study, classified in the three areas, estimated to be influential to decision making during the generation of objectives.

5.3.1.1 Basic Insights

Increased complexity of the car as a product has increased the complexity in related engineering activities. This complexity leads to an augmented need for decisions regarding objectives. This basic notion could be extracted particularly from quotes of employees with long years of experience. Decisions have to be made on all hierarchical levels; this includes the case worker on the bottom of the organisational scale of employees as well as the managers with personnel responsibility. Decisions differ in scope and momentum. Case workers are in most cases in charge of decisions in the problem solving process to elaborate a specific objective. For example, this can be a decision on which information needs to be looked at when calculating the potential difference in weight a new car shall have compared to its predecessor. Results from these decisions are then usually proposed to the next higher level, the team leader. He decides on the validity of the suggested objective and contributes in cross departmental meetings to reconcile reconciling the single objectives, sometimes supported by the case worker. Such meetings aim to release the current state of the system of objectives as a proposition for a first product specification to the development board. Such decisions may give rise to increased ambiguity due to the different stakeholders contributing to the decision. This entire system of objectives for a new product acts as the basis for a first product specification discussed in meetings of the board. The last decision in this case rests with the senior executive president of development, the chairman of the executive board, who decides whether the proposed system of objectives is to be pursued in further product engineering or if changes need to be made. In this case, adaptations on the bottom level of the decision ladder are necessary. The hierarchy for a decision depends on results of reconciliation meetings and relevance of the decision on the entire product. If there is disagreement, e.g. on the priorisation of objectives (e.g. fuel consumption vs. performance), this decision is usually transferred to the next level.

Transparency in interdependencies between objectives and associated information as well as in the steps taken in the generation of an objective are regarded as a significant problem to decision making in early stages. Thus a lot of decisions on *systems* of objectives are characterised by a so called “cherry-picking” of the decision makers, who, mostly intuitively, evaluate the situation by using just a number or even only one objective, ignoring dependencies to other objectives. A further problem is the dynamic change of relevant information and content of the system of objectives due to high uncertainty and little product knowledge in early engineering stages.

5.3.1.2 Individual procedures and activities

Engineers were interviewed regarding their individual procedures when working on the generation of an objective or on the analysis or prognosis of the environment. Insights were expected on differences in the influence of systematic rather than intuitive work and of the degree of standardisation of the processes, methods and tools used on the resulting objectives and environmental prognosis. Questions further focused on identifying potential differences in approaches taken by individuals or departments and how such procedures differ between projects for the same individual or department.

Regarding individual procedures to generate an objective or an environment analysis or prognosis, employees perceive themselves to be systematic in the steps they take or the choice of tools they use. Some blame changing project constraints and high levels of uncertainty as an issue that can compromise their ability to proceed systematically. The degree of standardisation is regarded as insufficient by most of the interviewees. Most conceive that there is nearly no standardisation in way and sequence in which activities are carried out, methods are applied and in the tools that are available. They state that there exists no officially defined process for developing objectives and integrating results of environmental research into objectives. The same interviewees find the entire early stage to be intangible, not knowing who is responsible for which result. They perceive the process to consist of rather implicit and detached work steps. Such statements are mostly found among interviewees at lower hierarchical levels. In the same departments, team leaders sometimes perceive the same activities as being standardised, although not officially documented.

Only the direct question whether there are activities always conducted during the generation of an objective, made some interviewees aware that they never wondered if there may be any generisable approach to in perform activities. Some departments partly make the sequence or content of activities they use explicit e.g. in process descriptions, which are regarded to be helpful. The benefit is seen to lie in a definition of intermediate results to be delivered, rather than in explanations of each work step. Some departments have a consistent degree of standardisation in procedures, such as the department responsible for the weight of cars. The procedure of deriving an objective for the weight of a new car is the same for all individuals in the team, but different to the steps individuals in the department for aerodynamics take to obtain an objective. It is assumed that the different nature of objective parameters demands a different procedure, which can be more or less standardised. Differences in the degree of standardisation can also be ascribed to the intensity with which a specific department has already tried to standardise procedures and to use specific methods or tools. There is a broad opinion that a standardisation of all processes, methods and tool is not possible, and not even desirable.

This is justified by the presence of highly dynamic constraints and uncertain information, which may impede a standard workflow and force employees to apply individual problem solving approaches and knowledge. Few methods and tools can be used from the later engineering stages, since most of them require a higher level and more specific information than is available in early stages. More methodological and tool support is regarded as essential to improve the way decisions are derived.

5.3.1.3 Information Base

Along with the degree of how systematic or standardised procedures are conducted, it was assumed that the information base available to a decision maker is influencing the outcome of a decision. Interviewees were questioned about information they need for their work, which information is available and how they handle it.

For *eliciting* information, external and internal sources are used. Sources are mainly publications, internet or personal contacts. For an environment analysis, information regarding trends, technologic development and the relevant competition is gathered.[346] For generating an objective, objective and series values for parameters from the preceding product are relevant as well as already existing current values of the objective and the cost and time schedule. Most interviewees perceived that information from the environment analysis and prognosis is not always integrated in their own objectives, possibly because of the lack of a process description.

Based on the assumption that the *state of information* influences the outcome of decisions, interviewees were asked to evaluate the development of the state of the information which they handle in the process. This development was to be drawn as a graph in a diagram, covering the time span between the first impetus for a project to the official formulation of a first product specification (early stage). This diagram was to be drawn for two parameters assumed to have an impact on decisions.[347] *Measurability* as the degree to which existing information is quantified and *reliability* as the degree to which this information is trustworthy. Figure 5-6 shows three representative examples of graphs drawn. Interviewee C drew a curve typical for answers of interviewees performing environment analysis and prognosis. He argued that initial activities are usually concerned with collecting mainly qualitative information. When information is analysed and constraints, i.e. their dependencies are predicted, the information handled is more quantitative. This resembles the development of information reliability, which improves the more uncertainty is reduced due to more knowledge about the product and exogenous constraints.

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[346] cp. to the evaluation of the previous case study
[347] This assumption bases on the findings of the literature review in section 3.1.5 and 3.1.5.3.

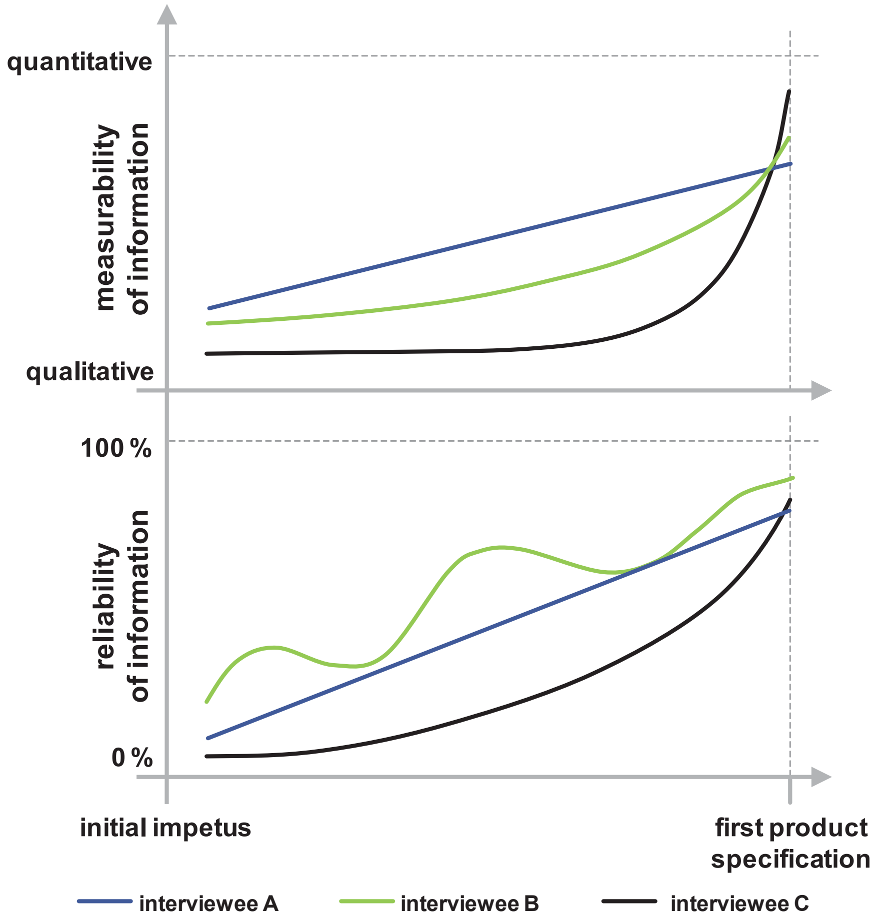

Figure 5-6: Examples of perceived measurability and reliability graphs

Interviewee B justified the alternating highs and lows of the curves by intermediate reconciliation meetings, in which new decisions were made and the reliability of associated information was needed to be restored afterwards, before obtaining an increased overall reliability. The differing starting points of the curves are reasoned with a differing initial information and knowledge base, which depends on whether the product to be developed has a predecessor or is a new project.

Regarding the *handling* of information further individual differences can be identified. Most individuals proceed differently with the information they elicit, document or save in a repository. Differences can be traced back to personal preferences or habits of handling data, which employees might have developed over many years. Examples for saving information are MS Office documents (MS Word, Power Point or Excel) or databases. Such documents are located either on the local computer or are accessible by others on network repositories. The repositories or databases are mostly only accessible for members of one department. There is no overall database linking information on the generation of objectives or the objective values themselves. Most departments do not have a standardised approach to handling information. This is justified on the basis of the highly differing information between projects and departments with varying content and quality.

Thus data management approaches as used in later development stages cannot be adapted. It is reported that the most currently used databases are outdated and are not able to handle further developed requirements of activities, e.g. to depict complex dependencies between objectives and related information. Such shortcomings cause reconciliations of results, especially between different departments, to happen only late in the process. This is also due to the high level of data to be processed. Another barrier to reconciliation caused by data handling is the circumstance that a lot of individuals tend to publish their results only when absolutely necessary, e.g. when they themselves consider the quality of their results to be sufficient. This may lead to different individual quality levels for results to be used in reconciliation meetings.

Particularly critical for decision situations is the *form* in which relevant information is provided; this can be of particular importance with regard to how easy conclusions can be drawn. Different departments use different solutions to this issue, such as the use of certain reports, diagrams etc.. There is an overarching opinion that none of these solutions serves as an optimal visualisation approach for discussion and decision making. Difficulties particularly lie with the transparent description of (qualitative) information concerning objectives, constraints and their dependencies. This is especially difficult if this includes information which has not been made explicit by other individuals. Besides not being available for others, the acceptance of results suffers since the derivation and argumentation of results might not be reproducable. Decision makers at higher management levels reported that they preferred sets of information, e.g. presentations, in which the degree of detail was tailored to the relevance and scope of the decision to be made. They welcomed an explicit highlighting of changes to documents describing previous decision situations.

Prior knowledge is reported as important to analyse and predict the environment as well as for the generation of objectives. This was found to be due by the possibility to compensate uncertainty, i.e. lacking information or unknown dependencies by intuitively using prior knowledge and experience. About half of the questioned interviewees believed that such knowledge is important, that someone inexperienced is not able to fulfil equal tasks in only working systematically, with the methods or tools. Others state that a certain degree of structured work is needed to avoid getting stuck in the same old procedures without accounting for changed constraints. It was nearly unanimously believed that sharing of needed prior knowledge and experience decreases during a project and need for professional technical knowledge increases. Several interviewees assumed prior knowledge was helpful in decision situations in which available explicit information was not sufficient and lacking information or fuzzy dependencies needed to be accounted for. This seems to be especially valid for decisions made in higher management in which it is simply not possible for a decision maker to review all information associated with the decision to be made.

It is believed that good decision makers have well developed mental models and are able to draw on heuristics developed from previous situations. Thus they do not need as much detailed professional knowledge on certain (technical) issues as a case worker, who derived the result.

5.3.1.4 Communication and Reconciliation

The third area initially assumed to influence decision making in the early stages was communication and reconciliation activities. It can be stated that there is no official or agreed process for reconciling intermediate results or current states of elaborations between departments and in most cases not in departments themselves. The point in time within a project, forms, participants as well as the information used differs depending on the project or respective objective. The coordination of meetings for discussions on the system of objectives is done by one department. Further cross-departmental communication usually happens if one side has material to discuss and particularly if both sides feel the necessity to talk. Several interviewees expressed a preference to have not only specialists on one issue in talks on the system of objectives or single objectives, but also participants who are able to evaluate the effects on the entire product (emergent properties), particularly for consistency of the system. In part, discussions are perceived as being biased by later responsibilities of individuals for anobjective parameter in the further development of the car which imply the achievement of the defined objective value. A high number of interviewees reported that they are not fully aware of the information flows during the generation of objectives in the early stages. It can be stated that decision making depends on how well information is communicated along hierarchical paths. Another deficiency impeding decision making is a missing standard regarding communicating on objectives concerning formulations and visualisation. This is one reason for potential inconsistencies in a decided state of the system of objectives and can be led back to differences in communicated information between projects and departments.

5.3.2 Interpretation

On the basis of the insights gained from the previously described results, several factors could be identified that repeatedly influenced decision situations throughout the early stages in activities concerned with the analysis and prognosis of the environment or the generation of objectives. Due to the contingency of decision making and objectives, these factors consequently influence also validity, consistency and comparability of objectives, i.e. also the system of objectives.

5.3.2.1 Project Constraints

Changing project constraints were named as a reason for differing procedures and the difficulty of standardising methods and tools by nearly every interviewee. Causes are assumed to lie in heterogeneity of product concepts and that information needs differ whether the project in focus is a new Carrera, Cayenne or a totally new vehicle.

Furthermore, activities seem to be conducted in a more standardised way, the more generations a product has already gone through (cp. a new generation of the Carrera 911 to a completely new production series). The environment is perceived as being highly dynamic. Thus the same sources can not always be used and the state of available information changes within each different project. Nevertheless, project constraints represent the context for each generation of objectivesa (Figure 5-7). With regard to the current, omnipresent public discussion on the reduction of fuel consumption, this debate strongly influences endogenous constraints on a project, such as the motorisation strategy of the company. Before even starting with the generation of objectives, such information initiates first ideas for the generation of objectives. Besides setting constraints for one single objective, it can also be observed that such constraints create an implicit *hierarchy of objectives* (Figure 5-7). Such a hierarchy might suggest that a reduction of fuel consumption has higher priority as improvement of performance, even though other constraints might have not even been reviewed yet. Further activities are strongly dependent on such given dependencies between objectives, since an achievement of higher ranked objectives is implicitly ascribed to a higher relevance by individuals. This hierarchy was in the most part not made explicit.

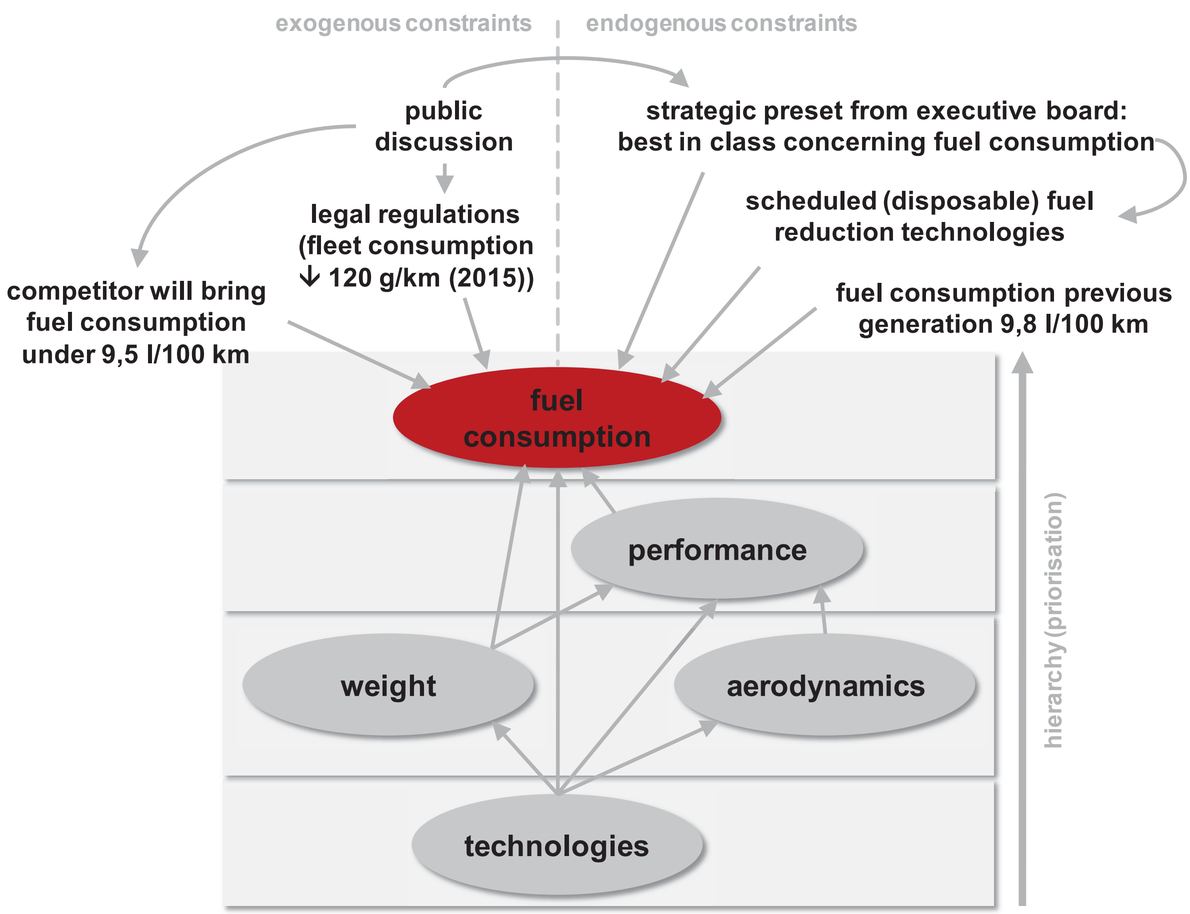

Figure 5-7: Example for contingency of constraints and implicit hierarchy of objectives

5.3.2.2 Prior Knowledge and Experience

Each interviewee held a different share of different forms of prior knowledge and experience. Following forms of prior knowledge and experience could be identified:

- *heuristic knowledge* representing an individual's mental models and generalised experience in the application of certain problem solving strategies
- *professional knowledge* concerning facts and the correct implementation of procedures, methods or tools regarding a specific subject area
- *company-specific knowledge* about processes and key people in the company, evolving throughout the time of employment of a certain individual

This knowledge is used in early activities, particularly for compensating for information or dependencies that are not available, uncertain or not tangible i.e. not measurable. The human mind is only able to process a certain number of dependencies. Thus, dependencies exceeding this number are either (consciously or unconsciously) ignored or assumed to be based on prior experiences. This becomes important when deriving a new vehicle concept in combining single objective parameters. As methods and tools to visualise or to consider dependencies in calculations are limited in the early stages, the evaluation of emergent properties such as driving dynamics needs to be supported using past experience and knowledge. The ability to effectively use prior knowledge in decision situations is particularly important for high level decisions, due to the limited time available to understand relevant details. Due to the high use of implicit knowledge, it is difficult to define the potential for standardisability of processes, tools and methods and argue for its implementation. Even though the execution of the processes without prior knowledge, using only systematic procedures, does not seem possible, articulation of implicit knowledge needs to be strived for to avoid an unsystematic and biased ordering of activities, leading to results lacking reliability and comparability.

5.3.2.3 Degree of Systematic Conduction of Procedures

Differences of individuals in the way they perform procedures affect reliability and comparability of results. Whether an individual proceeds rather intuitively or systematically in the pursuit of a task depends on his character and prior knowledge. Standardised processes, methods and tools provide a positive influence on the systematic execution of processes. Similarly, when using prior knowledge, a certain share of the activities executed are always characterised by the individuals´ response to unforeseeable uncertainties, changing project constraints and a consequently varying information base. In such situations, the individual needs to react flexibly. Results of activities, in particular validity and comparability, are likely to be influenced by the degree to which each individual conducts the activity systematically. Such differences in individual procedures impede planning of activities in advance.

5.3.2.4 Degree of Standardisation

The insights from the empirical study comply with studies on early stage design discussed in section 3.1.2.3. There is little standardisation of processes, methods, tools and also communication and reconciliation in and across departments. The early stages, in contrast to the later stages, are not clearly depicted in official process descriptions. The degree of (implicit) standardisation depends on constraints from the specific project, (assumed) priorisation (hierarchy) of objectives in the project and how systematically contributing individuals proceed. Development projects of products with a high number of previous generations are likely to be more standardised. The existing degree of standardisation or potential for standardisation is usually not explicitly known and is not consciously perceived by the participants of the process. This impedes the cultivation and development of standardisation. A lower degree of standardisation induces greater differences in the execution of individual processes, decreases comparability of results generated and increases uncertainty in corresponding decision situations. This uncertainty becomes visible, if at all, only in decision situations.

5.3.2.5 Transparency

Transparency in decision processes has a huge influence on the outcome of a decision situation. This includes transparency for the decision maker, how results were derived, which information was used and how intermediate and final results were reconciled. It is especially important that there is transparency in the provision of dependencies between subjects that are affected by the decision to be made. It is, for example, crucial to reveal potential inconsistencies which may result in a decision to change the objective for fuel consumption to a value which cannot be simultaneously achieved with the current objective value for weight. Transparency improves comparability and consistency of objectives. The earlier dependencies in the system of objectives are made transparent, the fewer iterations result due to emerging inconsistencies. Furthermore, transparency in the derivation of results fosters acceptance of the results, since chances and consequences of a decision can be more easily evaluated and it decreases uncertainty in decision situations.

5.3.2.6 Reliability

The reliability of information used for making a decision is dependent on its sources, the way in which it was derived (suitability of methods and tools used) and its inherent uncertainties. All factors are dependent on specific project constraints and the individuals working on the information. Objectives are derived using more or less reliable information. Thus, the validity of objectives is strongly dependent on the reliability of information used for their generation.

5.3.2.7 Availability

The availability of information describes the extent to which information that is needed is present in decision situations. Insights from the study revealed that the availability of information is also dependent on project constraints and associated uncertainty, e.g. sources relevant to a previous product generation might not be relevant for the new generation. In particular the way information and knowledge management is organised and standardised, influences the availability of information, for example, in databases or repositories. Moreover, the individual procedure on how much implicit knowledge is actually made explicit and thus available to others has a high impact on what information is in fact considered in the generation of objectives and decision situations. Information, which is not disposable or not even known to exist, cannot be accounted for, reducing the validity and consistency of results.

5.3.2.8 Measurability

It was observed that the more qualitative information was used during derivation of objectives and in decision situations, the greater the degree of uncertainty perceived by the participants. It was found that interviewees prefer to use prior knowledge and experience if disposable information is qualitative in nature and less tangible. Thus, differences in the degree of quantification of information associated with the generation of objectives influences the systematic execution of procedures as well as validity and comparability of objectives. Incorrect quantification of influences might also lead to reduced validity and inconsistencies in the resulting system of objectives.

5.4 Discussion of Findings

Previous sections outlined empirical results relating to how objectives and constraints are generated and factors influencing these activities. This section discusses results, regarding their generisability, by comparing them to similar existing case studies.

As a fundamental element of a first product specification, the generation of objectives is regarded as one of the most important tasks in early stages of vehicle development. The generation of the objectives is thought to integrate exogenous constraints, which are primarily developed by an analysis and prognosis of the environment. However, results show that this transition does not happen smoothly and in some cases objectives are insufficiently aligned to constraints arising from technologic development or potential competitor´s moves; this is confirmed by the studies of KHURANA and ROSENTHAL. The reasons were assumed to be related to the form and content in which the results from the analysis and prognosis were provided. A closer investigation identified the implicit and dynamic nature of engineering activities as a core problem. Since processes are not officially documented and changing project constraints force engineers to adapt activities to modified premises, process planning is impeded and seldom done.[348] As result, the execution of activities depends mainly on the project context,[349] is inconsistent and produces imprecise results.[350] Results of the study, regarding difficulties with strategies to mitigate uncertainty, are consistent with insights gained by EILETZ, who found uncertainties influenced the consistency of the final results. The evaluation further showed that current procedures lack a systematic identification and concretisation of information to cover future alternatives. Available knowledge is not evaluated regarding its inherent uncertainty and experience from past projects is not consistently used.[351] Another issue was the consideration of dependencies between constraints and their influence on objectives. As BRAESS and BADER similarly found, increased complexity of the product, *vehicle*, regarding its multitude of technologies and multidisciplinarity in engineering fields is not easily processable by individuals.[352] The detection and consideration of all cross connections by linking intermediate process results is difficult due to the implicit nature of dependencies and a lack of methodological and tool support in early stages, leading to inconsistent results.[353]

A central challenge in the early stages is the flexibility of processes, methods and tools necessary to encounter the dynamic environment. Such methodologies and tools are scarce and therefore uncertainties cannot be systematically accounted for. Studies of KAINDLA et al. equivalently find that this lack of flexibility may result in a decrease in the consistency of results and cause iterations.[354]

The insights from the study coincide with the findings of further studies, identifying the lack in transparency as main issue in early stages, causing important information to get lost on the way. This is a particular issue of the early stages, since a lot happens implicitly.[355] The articulation of changes and consideration of different future alternatives, accompanied by a reconciliation of informationis found to be important to achieve results of comparable and consistent quality.[356]

The execution of activities and use of methods and tools for generating objectives and for analysis and prediction of the environment depend highly on the individual, his prior knowledge, experience and degree to which he proceeds systematically.

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[348] see also Nuseibeh & Easterbrook 2000
[349] cp. to Verworn & Herstatt 2007b
[350] cp. to Khurana & Rosenthal 1997
[351] see also Eiletz 1999 and El Emam 1995
[352] cp. to Braess 1992, Bader 2007, see also Nuseibeh & Easterbrook 2000, Berkovich et al. 2009
[353] see also Kaindla et al. 2002a, Khurana & Rosenthal 1997
[354] cp. to Kaindla et al. 2002a
[355] cp. to Khurana & Rosenthal 1997
[356] cp. to Berkovich et al. 2009, Bubenko 1995

For example, the existence of prior knowledge might convince an individual that explicit analyses regarding a specific issue are not necessary.[357] This issue is enhanced by the implicit nature of the execution of activities, influencing communication and reconciliation processes. These differences in individual operations are caused predominently by differences in the information bases used to make decisions during the generating of an objective,[358] leading to a lower validity, comparability and consistency in the system of objectives.

The findings also coincide with the insights from KAINDLA et al. in that few suitable methodologies and tools are used. This is caused by a general reluctance to use sophisticated methods and tools, fearing their high cost and effort in getting used to them.[359] Advantages of such methods and tools are in most cases not known and their direct utility is not easily measurable, since an improved system of objectives will only show an effect when the product is finally (successfully) launched. [360]

After discussing the findings, the key question is what must be done to improve this state. To answer this question, conflicting factors need to be identified and understood as to why they have not yet been approached.

5.4.1 Standardisation versus Flexibility

Results revealed that activities, methods and tools, currently contributing to analysing and predicting the environment and to the generation of objectives, are characterised by a low degree of standardisation. This leads to a demand for more standards to improve comparability and validity of results. In parallel, due to prevailing uncertainty in early stages, constraints on projects constantly change. Thus, flexible structures are necessary to be able to adapt such a support to changing premises (e.g. process plans or databases). Currently, a lack of flexible processes, methods or tools is compensated by contributors using a lot of prior knowledge and experience. Thus, to assess these conflicting requirements and achieve improved comparability and validity, it is necessary to choose carefully the scope within which to standardise. Standardisation attempts need to support by providing a framework, e.g. for handling information and knowledge in a respective tool, to minimise avoidable mistakes (reduce epistemic uncertainty). It should leave sufficient room to apply individual knowledge to be able to react flexibly to unexpected situations; a possibility not available with standardised activities, methods or tools. Uncertainty in results should be explicitly revealed to provide a transparent information base for decisions.

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[357] cp. to Nuseibeh & Easterbrook 2000, Eiletz 1999
[358] cp. to Kaindla et al. 2002b, Almefelt et al. 2006, Berkovich et al. 2009
[359] cp. to El Emam 1995
[360] cp. to Bubenko 1995, Kaindla et al. 2002a, Sommerville & Ransom 2005

5.4.2 Systematisation versus Individuality

Systematic or intuitive progress is to a great extent dependent on the specific individual, their background and character. Thus, systematic procedures cannot be artificially imposed, e.g. by standardising methods or tools, but need to be individually developed as well as constantly and subtly supported. One way, based on insights of the study, is to use continuous intermediate reconciliations within a team. Recurring discussion and exchange of (intermediate) results may support a delimitation of the range in which results may vary, since different steps for the derivation of results can be discussed and convincing procedures may be adopted. There is no need to prescribe each activity in detail, concerning content and procedures, but it is important to agree on essential intermediate results in order to obtain consistent overall results. A compatibility of results may be ensured by discussion and by aligning them in meetings or by their transparent provision in stores accessible by all team members.

5.4.3 Implicitness versus Explicitness (Transparency)

This study confirms insights from other empirical studies of the early stages, which find not only the implicit nature of activities, methods and tools, but also handled information, knowledge and elaborated results, to be an inherent characteristic of this stage. In addition, transparency has repeatedly been identified as a necessary condition to improve results. The implicit nature of activities, information or knowledge is mainly caused by uncertainty. Moreover, each individual has a natural reluctance to disclose knowledge, either because he is uncertain about it or perceive it as an advantage to be lost when revealing the knowledge. This is equally valid for the exchange of information between departments. Thus, transparency is not generally claimable, but it needs to be subtly supported as far as possible by using suitable methods and tools. These need to support a considerate evaluation of that information or knowledge which is to be exchanged between contributing people. In particular, a transparent visualisation of objectives, their hierarchy and dependencies in a specific project should be strived for. Regarding project management, it is important to balance the extent to which activities are explicitly modelled and planned to support an efficient conduction of the process. The degree of transparency should be aligned to the prevailing decision situation and the necessary depth of detail to provide a suitable information base.

5.5 Implications for the Research Approach

The findings of the empirical studies at Porsche AG provide answers to the first research question on how objectives are generated and how constraints are considered in this process. Hereby, the insights support the postulations of the first research hypothesis.[361]

According to the findings

- objectives, their constraints and interrelationships between them are not made sufficiently explicit and thus generally not handled as *system of* objectives.
- the generation of objectives, constraints and their consideration in objectives happens in predominently implicit activities, which are not actively controlled.
- the generation of objectives, constraints and their consideration in objectives is affected by many influencing factors and their interrelationships (Figure 5-8).

This implicit approach causes a lack of awareness of the influencing factors by individuals contributing to the activities. Consequently, influencing factors are not consistently accounted for, knowledge on handling them does not sufficiently exist and related activities cannot be efficiently managed. Since the impact of these factors on the actual *system of* objectives is not clearly tangible, reliability, consistency and comparability of the system of objectives is impaired.

In order to improve this situation, it is necessary to define a holistic comprehension of the system of objectives, including objectives, constraints and their interrelationships. On this basis, a theory needs to be developed on how the distinct factors in practice influence the development of a system of objectives. On the basis of this knowledge, a strategy needs to be derived to describe how the influencing factors can be handled and the generation of objectives and consideration of constraints can be supported. Furthermore, an approach needs to be derived, which supports the implementation of that strategy in a real engineering environment.

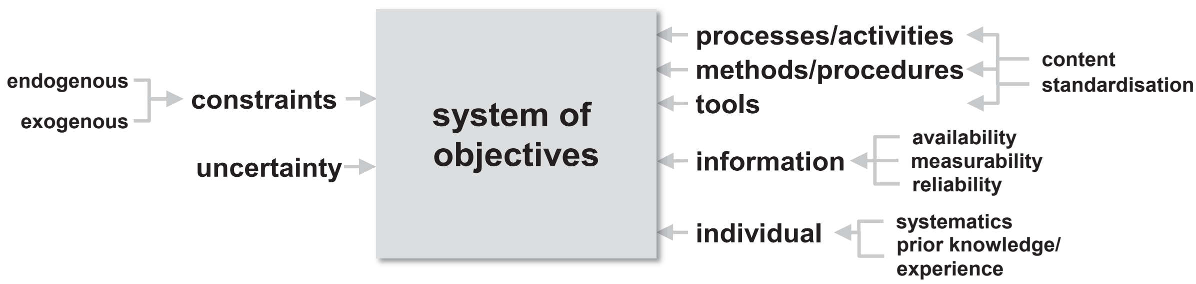

Figure 5-8: Influences on the system of objectives

[361] For further information on the empirical studies at Porsche AG, see Albers & Muschik 2010a, Albers & Muschik 2010b, Albers et al. 2010g,

6 The Development of Systems of Objectives

On the way to finding reasons which impair an adequate consideration of constraints in technical objectives, the previous sections clearly revealed that a major issue is the implicit nature and various influences on this process. On this basis, this chapter is dedicated to elaborating a theory on how these influences affect the development of an objective and how they can be dealt with. The theory is developed in four steps:

- *Relevance*: Outline the importance of finding a solution to the issue.
- *Static State*: Derive a unified comprehension of the coherence of objectives and constraints in their mutual system.
- *Dynamic development*: Establish a theory to be able to address the development of systems of objectives under consideration of influencing factors.
- *Strategies*: Define strategies to address and improve the development of systems of objectives in an engineering context.

This section argues that the support of the generation of objectives, on the basis of valid constraints, is essential to improve the target and market oriented development of products. This issue can be approached by conceiving objectives and constraints to be incorporated in one system and describing the development of that system as the reduction of uncertainty. An improvement to that process can be achieved by actively manipulating influencing factors to minimise uncertainty and to design a flexible support to cope with unforeseen uncertainty.

6.1 Relevance of System of Objectives

Chapter 1 specified the basic problem defining this research as consisting of three parts: the valid and encompassing prediction of relevant constraints, the translation of these constraints into technical objectives and the valid and consistent definition of objectives based on these constraints. This section discusses these issues with regard to their relevance for product engineering and argues that the use of technical objectives aligned to relevant constraints opens up significant potential for developing target and market oriented products. This is illustrated with data from a representative project conducted at Porsche AG (section 2.2).

6.1.1 The Role of Constraints and Objectives for Product Positioning

The limit of the grey plane in Figure 6-1 is defined by future core competitor vehicles, representing the competitive environment for a specific development project at Porsche AG, as anticipated in an environmental analysis and prognosis in 2007 (process description, section 5.2.1.3).

The red plane in the same figure depicts the actual competitors' vehicles released, thus the real competitive environment for the respective product, which was finally launched in 2010. Figure 6-1 uses the *multidimensional scaling method* to depict the position of competitors products and their own product relative to each other with respect to parameters such as *length*, *width*, *height*, *end face*, *wheel base, weight*, *power*, *cubic capacity*, *acceleration* and *fuel consumption*.[362] The three axes indicate the location of vehicles with specific parameter values and combinations. Vehicles along the *performance axis* are characterised by high power and acceleration values (e.g. Porsche AG vehicle), while cars along the *efficiency axis* focus on lower fuel consumption. This visualisation reveals clusters of vehicles with similar parameter values (e.g. competitors c and d). It allows the depiction of the vehicle development project in conjunction with its predicted competitive environment and a final evaluation of deviations from the anticipated to the eventual market position. This illustration depicts the anticipated future competitive environment at three different points in time in the development process (2007, 2008 and 2009) and its final state (2010). Thus it can be used to investigate the three basic issues identified above with respect to how they occurred within a specific development project. The constraint *competition* is hereby taken as example.

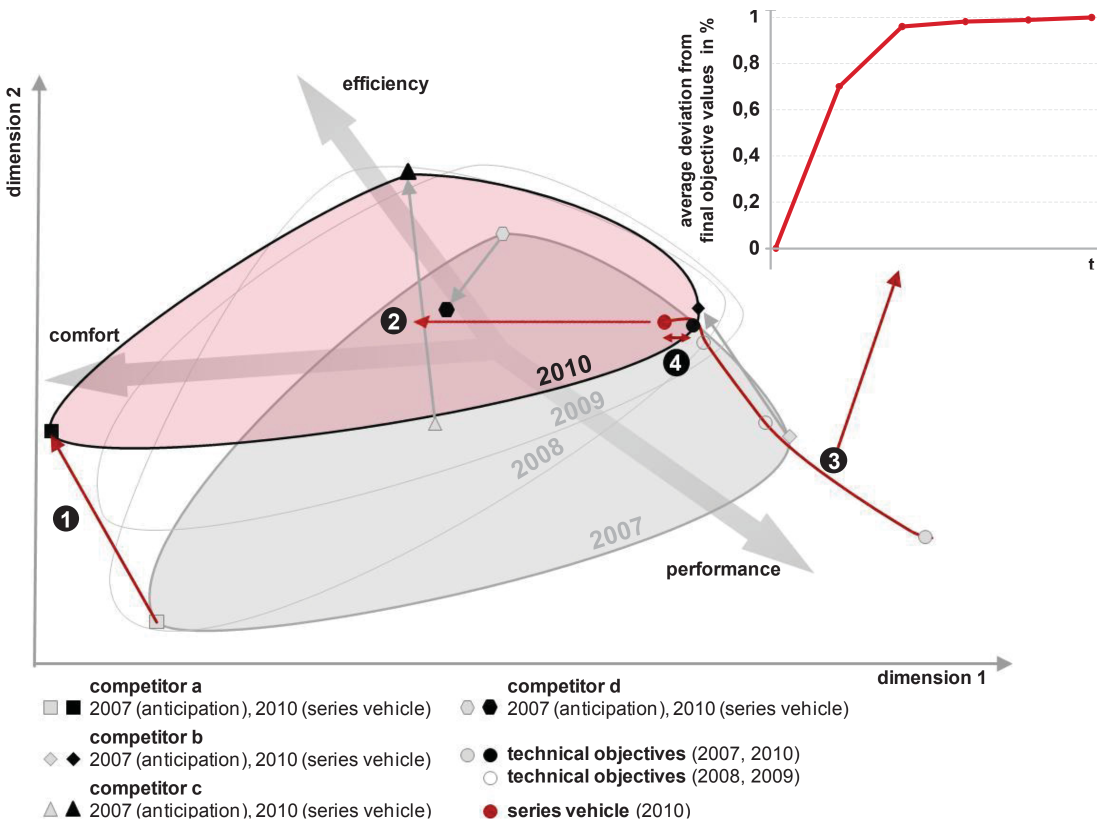

Figure 6-1: Predicted and actual product position in its competitive environment

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[362] for information on the content and application of multidimensional scaling, refer to section A.1.3

Planes in Figure 6-1 result, when competitors with the highest (predicted) parameter values on each axis are connected. The figure shows that this frame was initially anticipated to be performance oriented (grey plane, 2007), but competitor cars finally appeared to be rather more comfort and efficiency oriented (red plane, 2010) (❶). It further reveals that the anticipated distances between competitors resemble the final state, which indicates that the original prognosis had not been too bad in estimating one competitor's characteristic parameter combinations in comparison to other competitors (e.g. both planes show that competitor a is principally rather more comfort oriented in comparison to competitor d, who is rather efficiency oriented).

Car magazines regularly test several cars with a given competitive segment for their factual performance regarding particular product parameters and characteristics currently perceived to be important, especially for potential customers (e.g. factual fuel consumption, handiness). Besides customer queries, such tests from well known magazines are a common source for car makers to evaluate how their final series car performs in respect to its competition and what deficiencies in the car's concept are perceived. Results represent an important indication of how the market reacts towards a new product, i.e. how suitable the product is to meet current demands of potential customers. Results from an example press test, which examined all cars from the competitive environment as depicted in Figure 6-1, show that *competitor a* made first place, in particular due to a fine combination of comfort and driving dynamics. *Competitor d* made second place due to less comfort, but still well-balanced agility and torque. The vehicle of Porsche AG was ranked third, which was reasoned with reference to too little comfort due to a too hard suspension. These results can be reconstructed looking at the arrangement of vehicles in Figure 6-1. If the tendency to an increased level of comfort demand had been more strongly considered in the car concept and if it had consequently been positioned slightly further left in its competitive environment (indicated with❷), the final car would have potentially performed better in the test by whilst still keeping the Porsche characteristic peculiarities.[363]

If the development of technical objectives for the Porsche AG vehicle is tracked in Figure 6-1, it can be seen that these were constantly adapted each year (❸). The necessary adaptations decreased each year, supporting the perception of growing reliability of information throughout a project, which was stated by project participants in the empirical study (Figure 5-6). Furthermore, it can be seen that there is a small remaining deviation between final series values and objective values (❹). These findings lead to conclusions regarding the relevance of initially identified issues:

[363] cp. to Gulde 2010 (Auto Motor und Sport)

❶ *constraints*: a better anticipation of constraints (here: competition, identification of trends to stronger comfort and efficiency orientation) could have provided a more valid basis to define their own initial objectives values.

❷ *consideration:* a stronger orientation of objectives to constraints from the relevant competition could have enabled a better alignment of the product to the demands of the environment (even when using the incorrectly predicted constraints), less adaptations of objective values might have been necessary.

❸ *objectives:* the quality of objectives increases when product launch is approached (decreasing uncertainty). A better quality of initial objectives may provide better basis for a development with fewer deviations to objectives (❹).

6.1.2 The Function of Systems of Objectives in Product Engineering

According to ALBERS, the central activitiy in product engineering is validation. It is defined as the “continuous and systematic comparison of the accomplished objectives of the current situation with the planned state (objective).”[364] While the operation system performs the validation,[365] the system of objectives needs to provide the criteria, regarding which state of a product development project can be evaluated. These need to necessarily include criteria for the *validation of the product* itself and also of the *processes* required for its development. Product objectives delimit the solution space in which a product concept can be developed (Figure 6-2)[366] and process objectives define necessary activities, available time and resources for developing the concept. Besides ensuring that the system of objects is developed “right”, the system of objectives need to further make sure that in fact the “right thing” is developed.

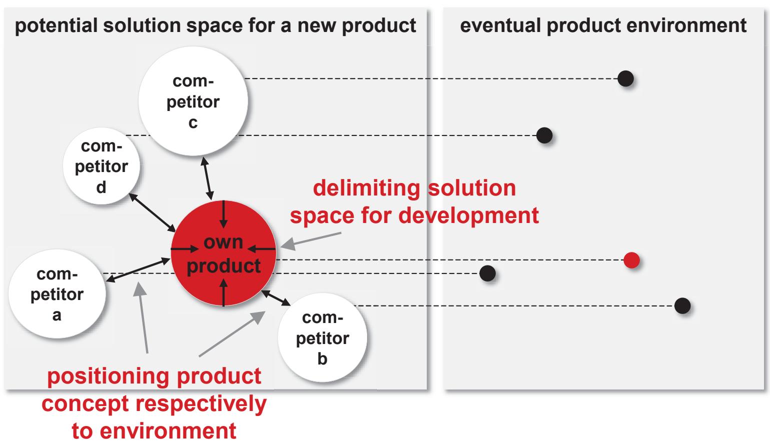

Figure 6-2: The two main functions of systems of objectives for product engineering

[364] cp. to Albers 2010, p. 5

[365] cp. to Oerding 2009 (validation of contents of system of objectives /system of objects), Chapter 7

[366] Figure 6-2 basically abstracts a potential competitive environment similar to Figure 6-1

Consequently, the system of objectives needs to fulfil a second function. It needs to provide the means to be validated itself (*validation of system of objectives*). Taking into account conclusions from the previous section, the means for validating objectives are defined by their exogenous and endogenous constraints. By considering constraints when defining objectives, objectives and thus the anticipated future product can be positioned relative to its predicted environment. Equally, the process objectives need to be validated against their corresponding constraints.[367]

6.1.3 Insights

Findings from this section highlight the particular relevance of systems of objectives for modern product engineering projects. While past engineering projects focused on developing what is technologically feasible, these insights propose an orientation of projects to future requirements of the respective product environment. This thesis takes the view that this is possible by an orientation of product engineering activities towards a system of objectives fulfilling the subsequent functions:

Definition 6-1: Function of Systems of Objectives in Product Engineering

- *validation of the system of objectives* to ensure the aspired position of the future product in its environment
- *validation of the product* by delimiting solution space to ensure target oriented development of the product

6.2 Static State of Systems of Objectives

The empirical studies (Section 5) revealed that one barrier to the generation of valid objectives sufficiently aligned to constraints was that most participants contributing to these activities did not perceive *their* objective to be a dependent part of an entire *system* of objectives. This was due to the fact that dependencies between objectives and relevant constraints were often not identified or remained implicit in the mind of individuals, and not disclosed to others. As shown in Chapter 3, existing research only provides approaches to depict objectives and their dependencies, not their relationship to constraints. Hence, before the effects of factors influencing the system of objectives can be assessed, a uniform description of the entire system needs to be derived to be able to address its state and development. The next paragraphs develop a unified understanding of systems of objectives based on formal, content related and temporal characteristics of contained objectives, constraints and their relations. An assessment of a system of objectives regarding its state (degree of concretisation, completion) and quality (validity, consistency, comparability) is proposed.

[367] this thesis subsequently focuses on product objectives

6.2.1 Elements and Relationships

The system of objectives is an abstract system, only implicitly existing as a mental model to represent the entity of objectives, associated information and relationships and to make this entity accessible for further reflection.[368] Thus, defining its elements and relationships is much more difficult than within real systems and is always based on and limited to the specific perspective of the approach used on the system itself. To ease the comparison with existing approaches, this analysis uses the common language and understanding, as defined in section 3.2.1, as a basis for our own insights to build upon. As defined by ALBERS, "the system of objectives describes all relevant objectives, their interdependencies and boundary conditions, which are necessary for the development of a correct system of objects. In addition, the reasoning of objectives is described."[369] This citation constitutes the basis for further reflection. According to this statement, each element of the system of objectives can be reduced to one of two basic *types* of elements, either an *objective* or a *constraint*. These two basic elements and their relationships can be distinguished as follows (see also Figure 6-3):

> **Definition 6-1: Objective**
> *Means to validate objects*: anticipated and aspired state of an object (e.g. main technical parameters, such as mass or fuel consumption)
>
> **Definition 6-2: Constraint**
> *Means to validate objectives*: associated information reasoning the generation and scope of objectives, delimiting the possible range of objectives and their values (e.g. exogenous constraints, like competition)
>
> **Definition 6-3: Relationship**
> A relationship indicates an assumed influence between two elements in a system of objectives. It can occur between two constraints (❶, Figure 6-3), a constraint and objective (❷), an objective and constraint (❸) or between two objectives (❹) and be bidirectional or monodirectional.

Taken together and regarded at one distinct point in time, all the elements and relationships of a system of objectives form one of an infinite number of potential states of the system. This is possible, since the system of objectives is dynamic and basic types of elements and relationships can occur in various different states.

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368 cp. to Chapter 3, see also Meboldt 2008, pp. 185/205

369 Albers 2010, p. 5, the term *boundary conditions* equals the term *constraints* and the term *correct* equals the term *valid* as used in this thesis

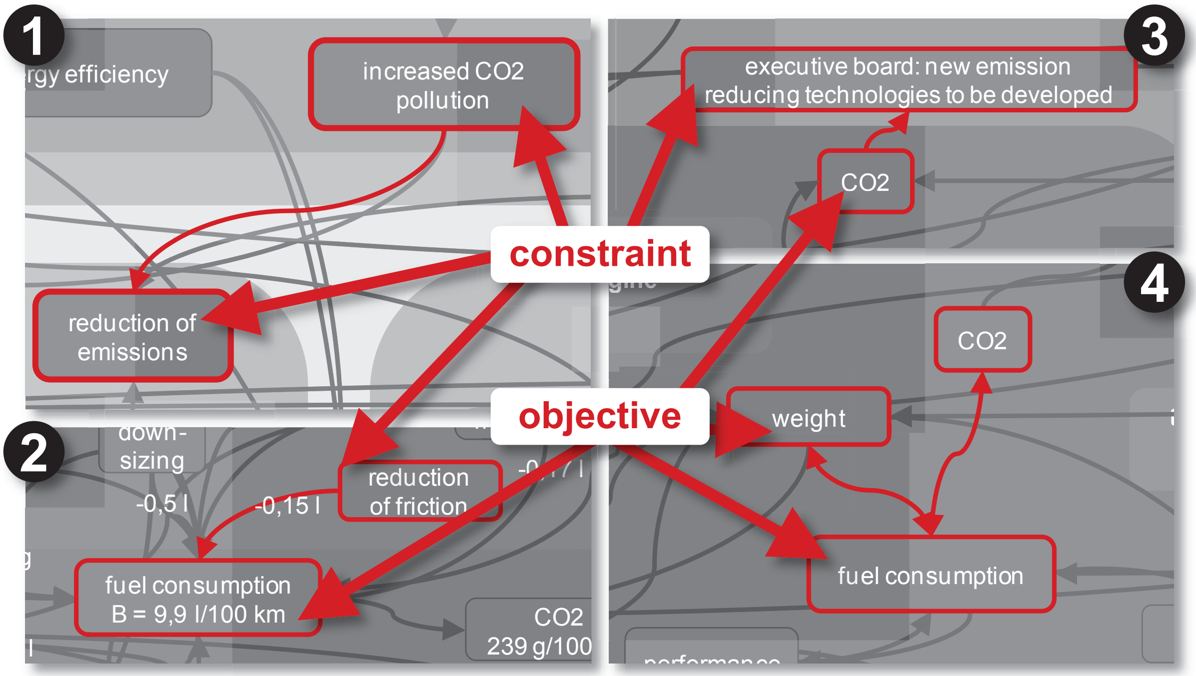

Figure 6-3: Different elements, relationships in systems of objectives (Definition 6-1 – 6-3)

The state is dependent on specific characteristics of an element at the distinct point in time. Each element has formal, content related and temporal characteristics as subsequently described.

6.2.1.1 Formal Characteristics

Formal characteristics of an element describe its formal composition. According to OERDING, each element of a system of objectives represents information, built from sets of characters and data as basic units to each element.[370] Equally, each relationship represents information (Figure 6-4). Drawing on the definition of information and knowledge (section 3.1.5.3), knowledge is information in its interlinked context. To integrate an objective or constraint into a system of objectives or to modify it, the individual processing the element needs to assume at least one relationship to already existing elements. For example, if the technology *thermal management* is entered into a system of objectives, the individual integrating it assumes that this technology has influence as a technological constraint on existing elements, e.g. fuel consumption (Figure 6-4). Thus, the introduction of each element into a system of objectives is necessarily influenced by, i.e. dependent on the knowledge of, the respective individual. Also, each relationship can only be defined if the two elements to be linked are already known.

[370] cp. to Oerding 2009, p. 130, see also section 3.1.5.3

> **Definition 6-4: Knowledge**
>
> Each element and its relationships represent information and can only exist in an interlinked context in a system of objectives. They depend on knowledge of the individual integrating or modifying an element or relationship.

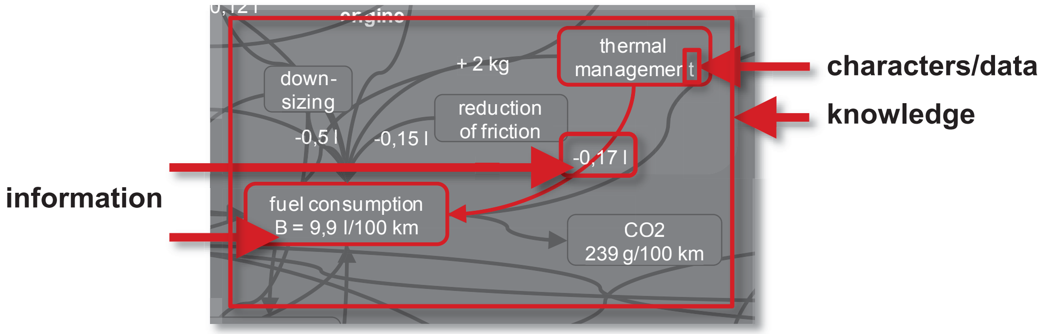

Figure 6-4: Different levels of knowledge

Since elements represent information, their formal characteristics can be described with the characteristic properties of information as outlined in section 3.1.5.3. The empirical study in section 5.3.2 revealed that *measurability* of information and knowledge was found to be particularly important for the generation of objectives. Measurability can be subdivided into the properties *quantifiability* and *clarity* (Table 6-1). *Availability* describes the different form in which knowledge of elements or relationships can be manifested, which is particularly important for the understanding of the actual extent of a system of objectives.

> **Definition 6-5: Availability**
>
> An element or relationship is implicit if it is consciously or unconsciously known to exist by an individual, but not directly expressed. An element or relationship is explicit if it is explicitly articulated (orally, written). A system of objectives usually contains both forms of knowledge.

Table 6-1: Inherent properties of information in systems of objectives (formal)

	information in elements	**information in relationships**
measurability		
quantifiability		
qualitative	“improvement of emissions”, no number/direction	technology a influences weight
tendency	“reduction of emissions”, decrease current state	technology a reduces weight
boundary	“reduction of emissions under 120 g/km”	technology a reduces up to 5 kg in weight
range	“reduction of emission to between 150 and 120 g/km”	technology a reduces 3-5 kg in weight
quantitative	“reduction of emissions to 120 g/km”	technology a reduces 5 kg in weight

clarity		
approximate	"reduction of emissions to around 120 g/km"	technology a reduces about 5 kg in weight
fuzzy	"reduction of emissions", to which extent?	technology a reduces weight
ambiguous	"improvement of emissions", decrease emissions or improve composition?	technology a influences weight positively or negatively?

The specificity of the formal description, also called *formal abstraction (specificity)*, of objectives, constraints and their relationships depends on whether they express project dependent or independent information:

- *project independency* – e.g. the trend *decrease of natural resources* and its relationship to the technological trend *reduction of emissions* is completely valid as a constraint for the development of an SUV as well as for a limousine.
- *project dependency* – e.g. information from a study revealing that there is a current *trend of automotive manufacturers to reduce emissions in SUVs* is, in addition to its relationship to the trend *decrease of natural resources*, classified as project dependent information.

6.2.1.2 Content Related Characteristics

Elements and relationships in a system of objectives can be characterised regarding their content, i.e. knowledge they contain. Since sections 3.1.5.3 and 5.3.2 revealed that *reliability* is an influencing factor in the generation of objectives, it is defined as an inherent property of information and knowledge in elements and relationships (Table 6-2).

A constraint or objective can address any possible object. However, there are three main classes that can be differentiated according to their basic character (Table 6-3). Elements with similar content are often (implicitly) clustered, since their relationships are fairly obvious, such as all constraints concerning a certain trend (Figure 6-5). The common content that all elements of a cluster refer to can be regarded as a superior classification level (e.g. all elements depict information on *trends*). Several clusters may be nested and form a hierarchy, e.g. the cluster *trends* is superior to clusters of *global trends* and *technological trends*. Elements can occur on any hierarchical level and are related to the superior level with an is-a or is-part-of relationship.

Table 6-2: Inherent properties of information in systems of objectives (content)

reliability	
validity of assumptions	correctness of premises assumed, when integrating, i.e. deriving the information
correctness of content	correct information, e.g. natural resources decrease vs. natural resources increase
completeness of content	complete content of information, which is available for one element, i.e. relation

Table 6-3: Different classes of objects addressed by elements

objects		
abstract	addresses a model of reality	e.g. a trend, ageing of population
inherent	addresses a property or feature	e.g. a parameter, reduction of fuel consumption
manifested	addresses a real object	e.g. a technology, introduction of start-stop

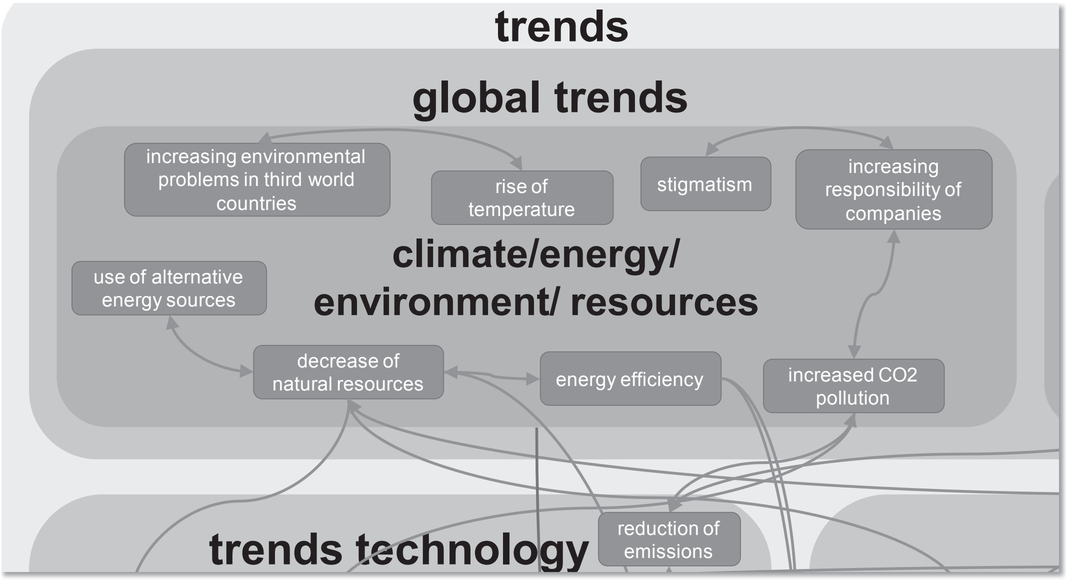

Figure 6-5: Cluster of constraints with content affiliation

The content of information and knowledge in elements of systems of objectives may be more or less specific. Depending on the level of specificity, an element may be related to more or less elements. For example, the trend *decrease of natural resources* has a fundamental influence on all other elements, whereas information on a regulation may only be relevant to one objective (e.g. CO_2-emission). This equally applies to the relationships. For example, the impact of a new technology as constraint on an objective might differ depending on the concept environment (e.g. influence of start-stop technology on fuel consumption differs depending on the product concept). The lower an element is situated in a hierarchy, the more specific is its content. The different outlined levels represent ranges in which characteristics of an element of a system of objectives can occur. Since the definition of levels of abstraction is always dependent on the prevailing conditions at the moment of definition, levels generally cannot be defined and need to be analysed in the context of a specific situation.

> **Definition 6-6: Structure and Hierarchy**
>
> Elements in systems of objectives build clusters of elements with affiliated content. Elements with content at different levels of specificity may form hierarchical levels within each specific cluster.

Table 6-4: Examples for different levels of abstraction of content for an element

elements		
general	valid as element of systems of objectives for any product	e.g. a trend, *decrease of natural resources*
product specific	valid as element of systems of objectives only for a certain product	e.g. specific product environment, *decreasing sales in SUV branch*
objective specific	valid as element of systems of objectives for a certain objective	e.g. certain regulations, *regulation on $C0_2$ emission*
relationships		
general	valid as relationship between two specific elements for any product	e.g. physical relation, e.g. *relationship between drag and end face*
product specific	valid as relationship between two specific elements only for a certain product	e.g. design relation, e.g. *relationship between implementation of new technology and objective*

6.2.1.3 Temporal Characteristics

Information and knowledge of elements in a system of objectives differ in the scope of time they cover (section 3.1.5.3). *Temporal validity* describes the span of time for which an element is assumed to be legitimate from a current view point. For example, a global trend is a phenomenon relevant for the next 20, 30 years and is essential for the strategic orientation of a company, e.g. to align a product portfolio regarding alternative technologies. Information of competitors, e.g. announced by the press might change in time, but might give hints for the differentiation of a new product.

Besides being temporally valid for a certain period of time, information in elements may address different distinct *points in time*, such as an anticipated regulation in 2017, constraining the objective for CO_2-emissions, addressing the intermediate future. These examples only represent examples of cases to illustrate possible points in the future which can be addressed by elements. Of course, for example, a new piece of relevant legislation can also be announced and apply to the near future.

Table 6-5: Different time spans covered by elements

temporal validity	
long-term	e.g. global trends*, urbanisation*
mid-term	e.g. technologic trends*, research on fuel saving technologies*
short-term	e.g. information of competitors*, cooperation with supplier xy*

Table 6-6: Different points in the future

addressed point in time	
remote future	e.g. trend scenarios*, in 30 years mainly electro mobility*
intermediate future	e.g. regulations*, update of EU emission regulation in 2017*
near future	e.g. competition*, launch of new SUV of competitor xy in 2012*

6.2.2 State of the System

Earlier paragraphs outlined the characteristics of elements in a system of objectives. To understand and assess its overall state and progress, e.g. to compare different states, it is necessary to be able to address overall system properties.

A system of objectives can be described regarding its characteristics *state* and *quality*.[371] To evaluate a system of objectives regarding these characteristics, parameters are needed to describe differences in these characteristics. The state of a system of objectives can be depicted by the parameters *completeness* and *concreteness*.[372] Completeness describes how many of the elements and relationships needed for a "complete" system of objectives are included in a certain state of the system. Concreteness depicts the information content needed in elements and relationships. The parameters are time variant. A gap between a best suitable (optimal) (100 % complete, concrete) system of objectives and a specific state in time can be defined as *uncertainty* due to lack of completeness and concretisation (Figure 6-6).[373]

> **Definition 6-7: State**
>
> The state of a system of objectives is characterised by its *completeness* and *concreteness*. The deviation between a current and optimum state is described as uncertainty.

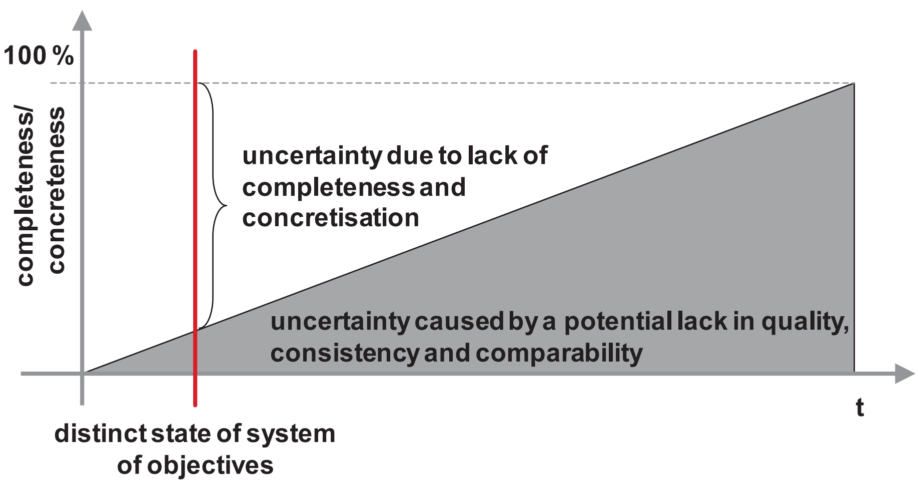

Figure 6-6: Development of completeness and concretisation of a system of objectives[374]

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[371] the state of a system can be described as attribute (characteristic) (Hall 1962)
German term for quality: „Güte"

[372] cp. to Meboldt 2008, p. 157

[373] scope, meaningfulness and attainability of a 100 % complete and concrete system of objectives in concrete engineering tasks is discussed in the next section

[374] based on Meboldt 2008, p. 157

Besides the state of a system, which can be regarded as variable for planning its development, its *quality* addresses its actual value in a distinct state. This distinction is necessary since a system might be relatively concrete and complete, but may lack *validity*, *consistency* and *comparability.* The parameters *validity*, *consistency* and *comparability* had been repeatedly mentioned in empirical studies as important characteristics to be strived for in a system of objectives. The previous definition of elements and relationships now provides the means to describe these parameters by specific states in characteristics of elements and relationships.

Validity is described by the reliability and measurability of an element or relationship. The degree of conflicts among objectives or constraints is depicted by the system´s consistency. Comparability describes the compatibility of formal and content related characteristics of different elements and relationships to each other. While the validity of the system can be measured by aggregating the validity of the single elements and relationships, an evaluation of consistency and comparability demands an analysis of the entire system. Deviations from a potential optimum state in validity, consistency and comparability cause further uncertainty in a specific state of the system (Figure 6-6).

Definition 6-8: Quality

The quality of a system of objectives is defined by its *validity*, *consistency* and *comparability* determined by characteristics of elements and relationships. A gap between a current and optimum quality is expressed as uncertainty.

While uncertainty due to a lack of elements or relationships is caused by missing elements or relationships, uncertainty caused by a lack of concretisation and deficiencies in validity, consistency and comparability can be led back to the specific state of the formal and content related characteristics of the elements and relationships (see next sections).

For either of these characteristics, the inherent uncertainty can be expressed using the criteria as defined in Table A-2, such as likelihood, possibility to occur or how believable or doubtful the information of an element or relationship, is.

6.2.2.1 Formal Characteristics

Table 6-7 summarises the formal characteristics of elements and relationships as described in section 6.2.1.1 having an impact on uncertainty in systems of objectives.

Table 6-7: Formal characteristics in elements and relationships causing uncertainty

lack in concretisation		
inherent properties	state of measurability	e.g. influence of a technology on an objective only known qualitatively
lack in validity		
inherent properties	state of measurability	see examples in section 6.2.1.1
lack in consistency		
consistency (formal structure)	formal description is not consistent	
lack in comparability		
compatibility	formal description of elements and relationships is not compatible	

6.2.2.2 Content Related Characteristics

Table 6-7 summarises the content related characteristics of elements and relationships as described in section 6.2.1.1 having an impact on uncertainty in systems of objectives.

Table 6-8: Content related characteristics of elements and relationships causing uncertainty

lack in concretisation		
content specificity	insufficient degree of specificity of content	e.g. the mechanism of a predicted technology is not sufficiently specified
lack in validity		
inherent properties	lowered validity of assumptions	e.g. # of vehicles with V12 engines rises by 2015
	(partial) incorrectness of content	e.g. increase of natural resources
	(partial) incompleteness of content	e.g. rise of 11 % (of what?)
lack in consistency		
consistency (content)	content of related elements is not consistent	e.g. increase in weight neglected when considering technology in objective
lack in comparability		
compatibility	assumed premises of derivation not compatible	e.g. different points in time for compared elements

6.2.2.3 Temporal Characteristics

Neither the temporal validity nor the temporal scope of an element or relationship affects the uncertainty caused by a lack of completeness, concretisation or quality.

6.2.3 Insights

This section gave an overview of the characteristics of systems of objectives. It did not attempt to outline a “complete” system of objectives, nor did it provide a prescription on how to correctly define or structure elements and relationships. It aimed to provide a unified description of all implicit and explicit elements and characteristics of a system of objectives, including objectives as well as constraints. The discussion showed that systems of objectives comprise two basic elements, objectives and constraints, which can be equally described regarding their characteristics. A system of objectives can be described by the three dimensions *structure*, *hierarchy* and *state*. Structure and hierarchy are determined by characteristics of the elements and associated relationships, the state of a system of objectives can be described by the remaining state of uncertainty, i.e. a lack in completeness, concreteness and quality. Assuming that uncertainties incorporated in a system of objectives are targeted to be reduced in the engineering process, the question emerges on how the generation of a system of objectives can be improved by supporting its completion and concretisation, while simultaneously accounting for its quality. This question can be assessed by previously finding an answer to the (concretised) research question 2:

Research Question 2 (extended)
Which influencing factors (section 5.5) impact the state (concretisation and completion) or quality (validity, consistency and comparability) of a system of objectives and in what way?

6.3 Dynamic Development of Systems of Objectives

One issue addressed in this thesis is the lack of transparency about what impedes the generation of valid technical objectives whilst considering relevant constraints. Past sections revealed major factors influencing this process and provided a means to approach objectives and constraints coherently within a system of objectives. On that basis this section analyses how such systems develop with a focus on the *generation* of objectives and how this development is influenced by these factors.

Thus, the characteristic activities of this process need to be analysed in order to identify how specific factors, such as certain methods or an individual, influence the state and quality of a system of objectives within each activity. However, past insights have revealed that a generic sequence of activities describing the development of objectives cannot exist due to constantly changing project constraints. To overcome this issue, and still be able to analyse the development of a system of objectives, it is necessary to draw on the findings of section 3.1.4.

Decisions were found to play a key role in the generation of an objective. Since decisions need always to be considered as part of a superior problem solving process, problem solving activities can be understood to be fundamental steps in the development of a system of objectives. Thus, the problem solving cycle, according to ALBERS[375], can be used as a generic framework to investigate steps in the development of a system of objectives. This section argues that this development is dependent on the development of its associated uncertainty. This uncertainty itself is then contingent on prevailing influencing factors, of which some can be actively manipulated.

6.3.1 Problem Solving Activities

6.3.1.1 Situation Analysis – Initial State and Collection of Information

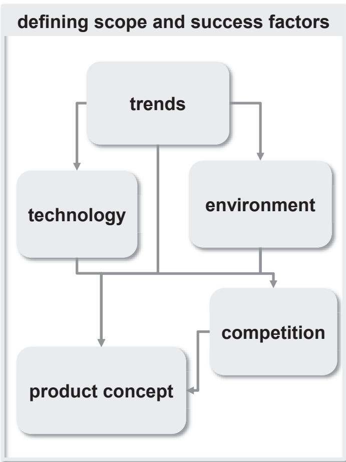
The initial activities to generate objectives are dedicated to eliciting the information which is needed to derive objectives for the associated development project. This may be information that already exists in a company or which is identified as lacking and necessary to build a suitable knowledge base. To limit the range of information, required, the definition of the scope for the specific system of objectives has to precede this activity. Due to the fractality of problem solving activities, this first step in the situation analysis can itself be regarded as situation analysis.[376]

[375] SPALTEN, see Albers et al. 2005a and sections 3.1.5 an 3.2.3.2

[376] see Albers et al. 2010b and further discussion in section 7.3

The scope of a specific system of objectives depends on the conditions for the specific project for which objectives are to be derived. Among these are the points in the future believed to be of particular importance, i.e. date of market launch, and the period of time the product to be developed is supposed to compete in its market. It also depends on factors regarded as important to the success of a product, such as customer satisfaction, market or technologic leadership. This scope determines the degree of completeness and concretisation of the system of objectives ideally to be achieved to enable a responsible engineer to make critical decisions in a certain decision situation. The degree of completeness to be achieved comprises all the knowledge needed concerning relevant constraints for the future product, covered by the identified scope (e.g. success factors, market leadership, and all the related constraints resulting from the respective competitive environment, Figure 6-7). The degree of concretisation results from assumptions made regarding the decision situation and knowledge required (for which decision situation shall the system of objectives be consulted, e.g. first product specification or finalised product concept).

This initial scope defines the initial knowledge to be developed and corresponds to the initially existing *epistemic* (reducible) uncertainty in the system of objectives (Figure 6-8). All factors not considered as part of the scope represent the existing *aleatory* (irreducible) uncertainty with respect to the future described state and the need to be treated as such (section 3.1.4.2).



completion ↑↑	concretisation ↑↑	quality ↑↓	consistency ↑↓	comparability ↑↓
• **constraints**	• **constraints**			
• **process** standardisation	• **process** standardisation	• **process** content	• **process** content	• **process** standardisation
• **information** disposability, reliability	• **information** disposability reliability measurability	• **information** reliability measurability	• **information** disposability measurability	• **information** disposability
• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge
• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**

Figure 6-7: Influences during activity *defining scope and success factors*[377]

[377] Arrows in the headline indicate the direction of change in a parameter due to an influencing factor. E.g. *completion*: the system of objectives is completed more or less in this activity due to e.g. availability of information, quality de- or increases due to e.g. an individual's knowledge. Examples in the left part of the figure refer to information from the example project previously used.

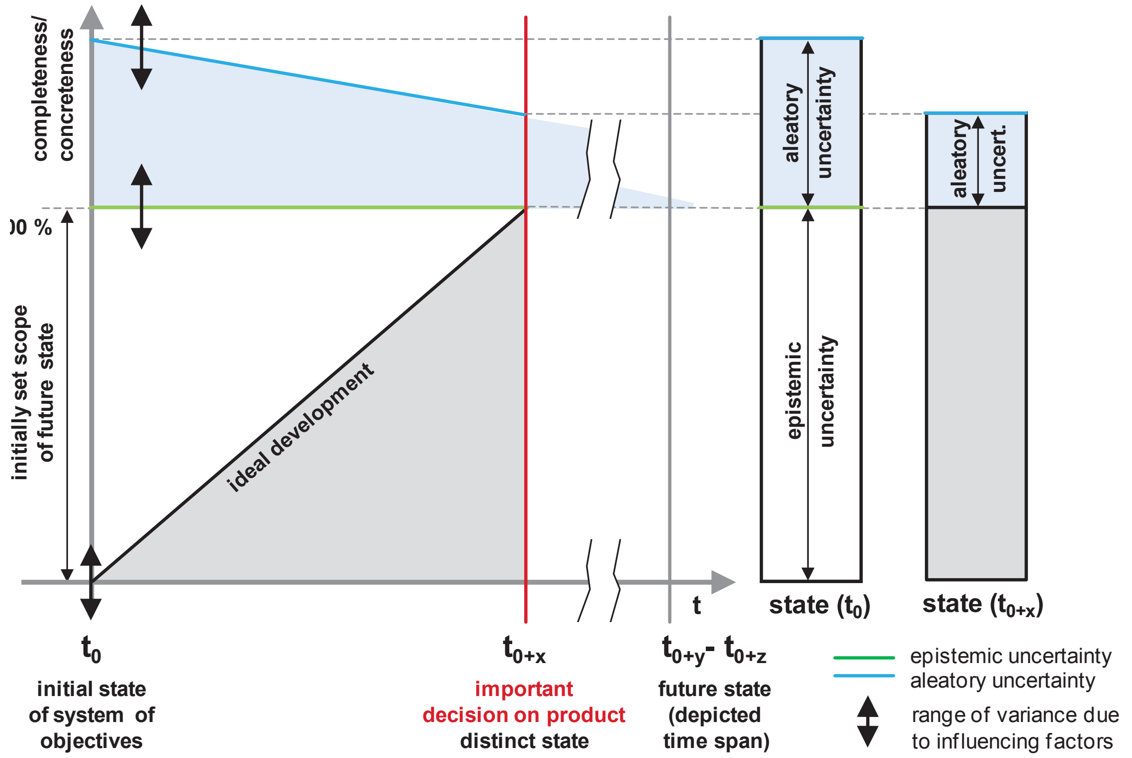


Figure 6-8: Overview of the initial scope for *concretisation* and *completion* of the system

Aleatory uncertainty decreases with the reduction of the time gap to the anticipated state, since possibilities for occurrence and combination of potential risk factors decrease.[378] There can be no objectively correct setting of the scope, since factors and influences relevant in the future cannot be completely identified and predicted. However, the more comprehensive and concrete an initial scope is defined, i.e. the more relevant factors are identified and considered, the greater the share of epistemic uncertainty which can be reduced by accumulation of knowledge. Those success factors that are in practice considered and prioritised depends on the philosophy and line-up of the company as well as constraints currently regarded as important (e.g. ecology), available information to support these factors and the existing prior knowledge of the judging observer. As shown in Figure 6-7, success factors considered are initially the content related clusters of the system of objectives (section 6.2.2.2) and are thus its initial definition i.e. degree of concretisation.

The system of objectives is limited by its scope.The initial scope is of particular importance to determine the quality of the system of objectives believed to be necessary for a decision situation. The migration of the initial quality of the system of objectives to ideal quality can also be described by modification of epistemic uncertainty (Figure 6-9).

[378] cp. to section 3.1.4.3 and Figure 3-5 (scenario planning)

An objectively ideal degree of quality can also not be defined, since the validity of the elements of the system of objectives can only be finally evaluated when the anticipated state is achieved in the future. Thus, the required quality is always defined subjectively, depending on available information and its properties as well as potential regulations from the company, e.g. by documents for a decision situation and their format. The initial quality is further dependent on existing official regulations within associated process steps, the procedures with which the scope is derived and the information available and previous knowledge of the engineer (Figure 6-7).

The scope, which is significant for the development of objectives, is not always set consciously, but may exist implicitly in the engineers´ minds, e.g. from prior knowledge. Thus, state and quality to be achieved are not always explicitly defined.

Definition 6-9: Scope of a System of Objectives

The initial scope is of particular importance to the degree of completeness, concretisation and quality assumed to be required by a system of objectives for a targeted decision situation. It is predominently dependent on a future point in time and success factors assumed as relevant, on the company, constraints and responsible engineers. Thus, it is not objectively definable and not always consciously set, but crucial for the remaining uncertainty to be reduced throughout the development of the system of objectives.

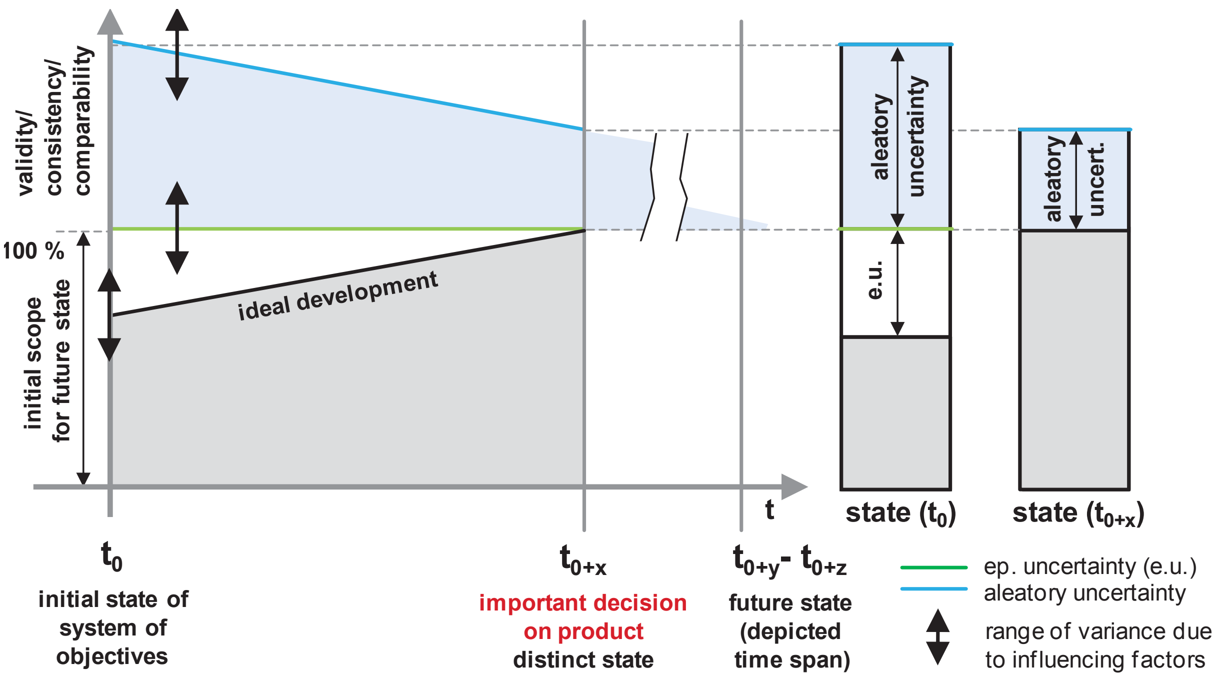
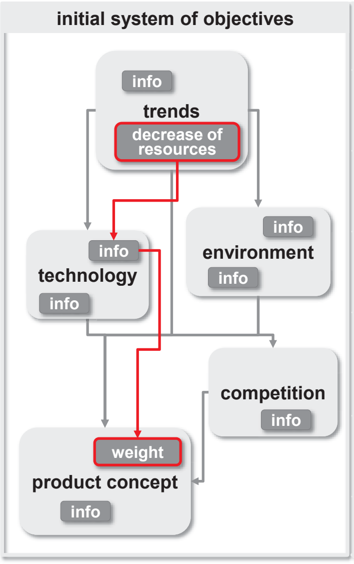


Figure 6-9: Overview of the initial scope for *validity*, *consistency* and *comparability*



completion ↑↑	concretisation ↑↑	quality ↑↓	consistency ↑↓	comparability ↑↓
• **constraints**	• **constraints**			
• **process** content standardisation	• **process** content standardisation	• **process** content	• **process** content	• **process** standardisation
• **methods** content standardisation	• **methods** content standardisation	• **methods** content	• **methods** content	• **methods** standardisation
• **tools** content standardisation	• **tools** content standardisation	• **tools** content	• **tools** content	• **tools** standardisation
• **information** disposability reliability	• **information** disposability reliability measurability	• **information** reliability measurability	• **information** disposability measurability	• **information** disposability
• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge
• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**

Figure 6-10: Influences during activity *finding initial system of objectives*[379]

Based on the initial scope, information regarding identified relevant factors (e.g. trends, competition) is elicited to reduce the prevailing state of uncertainty. It is consciously or unconsciously defined depending on which and how much information is required, how concrete the information has to be and which information is already available.[380] Information existing from previous, similar projects or known constraints, such as the company´s long term strategies, is matched with clusters predefined by the initial scope (Figure 6-10). The extent to which information is in fact identified as suitable to this scope and matched to the clusters depends on the content of existing processes, methods and tools. Further influences are the availability of information, knowledge of the individual about the existence of the information, i.e. knowledge, e.g. in repositories or in other individual´s minds, and how they match knowledge from prior projects with content relevant areas for the scope of the task. At this stage of development, the system of objectives may exist explicitly in tools, e.g. databases, or implicitly in the mind of the developer, or both. After identifying the gap between available and missing information, the potential steps, procedures and tools required to collect missing information can be identified, evaluated and selected[381]. This depends on standardised procedures or tools, the knowledge regarding procedures and prior experience. The eventual decision to use a procedure or tool is affected by the department or companies existing and individual knowledge.

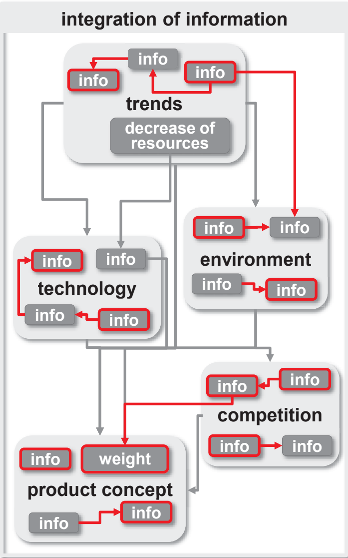
[379] new or modified elements in the left part of the figure are highlighted in red

[380] These actions represent the activity of *problem containment* as next step in the superior activitiy *situation analysis* after the previous *situation analysis* (definition of scope and success factors).

[381] These actions correspond to the problem solving steps *search for alternative solutions*, *selection of solutions* and *analysis of the level of fulfilment* in the superior activitiy *situation analysis.*

The collection of information is done actively, by searching for information in available sources such as publications or the internet, or passively, e.g. by receiving knowledge in talks with individuals.The choice to integrate elicited information into the system of objectives, in particular, depends on the state of the information (constraint) itself, methods used and procedural directives. Thus, information is either explicitly (e.g. documents) or implicitly (mentally) integrated into the system of objectives. It is consciously or unconsciously matched with existing clusters and linked with existing information, for example, new studies on trends are assigned to older studies (Figure 6-11).[382]

The degree of concretisation depends on properties of the information in the state in which it is integrated (e.g. reliability of information from a specific newspaper) and how it is interlinked, which depends on prior knowledge and individual procedures. Thus, the quality of this activity is influenced by the methods used, tools and individual procedures. The collected information is then compared to the required information.[383] If there is a discrepancy, procedures used, tools or sources are either adapted and further information is collected or the discrepancy is accepted, i.e. ignored. The deviation may not even be known if the initial scope was not consciously set.



completion ↑↑	concretisation ↑↑	quality ↑↓	consistency ↑↓	comparability ↑↓
• **constraints**	• **constraints**			
• **process** content standardisation	• **process** content standardisation	• **process** content	• **process** content	• **process** standardisation
• **methods** content standardisation	• **methods** content standardisation	• **methods** content	• **methods** content	• **methods** standardisation
• **tools** content standardisation	• **tools** content standardisation	• **tools** content	• **tools** content	• **tools** standardisation
• **information** disposability, reliability	• **information** disposability reliability measurability	• **information** reliability measurability	• **information** disposability, measurability	• **information** disposability
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• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**

Figure 6-11: Influences during activity *integration of information*

[382] These actions correspond to the problem solving step *decision and implementation*.
[383] These actions represent the problem solving step *recapitulation and learning*.

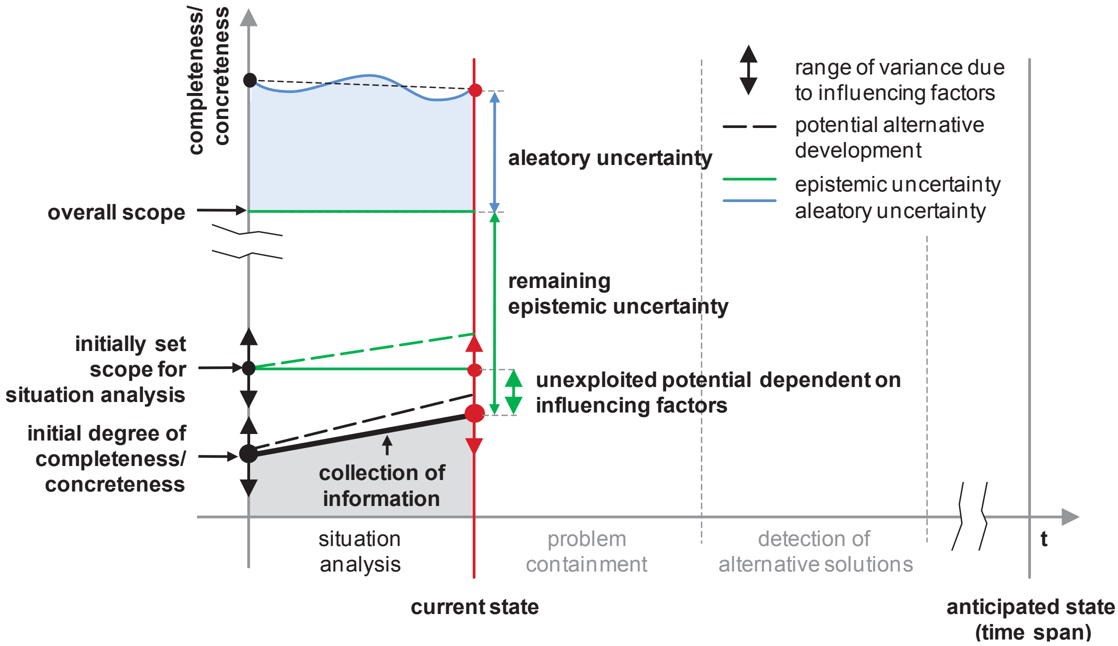


Figure 6-12: Development of system of objectives during activity *situation analysis*

The effects of the influencing factors on the reduction of uncertainty in the system of objectives as discussed in this section have been transferred into the diagram first introduced in Figure 6-8. Figure 6-12 indicates the development of aleatory and epistemic uncertainty during this activity and shows the ranges of variances of potential uncertainty reduction influenced by the eventual use and occurrence of influencing factors. It also outlines potentially remaining uncertainty after this activity.

6.3.1.2 Problem Containment – Analysis of Information

Another activity during the generation of objectives is the analysis of collected information, regarding its coherence and evaluation concerning its relevance and validity for decisions within the development project. Initially, the scope of the analysis is defined, i.e. which task is to be analysed and for what purpose the analysis serves in respect to the generation of objectives (e.g. identification of past trends as basis for predictions). The overall scope, taken as the basis for this activity, may deviate from the initially defined scope if the activity is performed by a different individual or if constraints, assumptions or the availability of information has changed (Figure 6-13).[384] The selection, choice and evaluation of suitable procedures and potentially useful methods and tools depend on these assumptions, prior knowledge from previous projects and the individuals who developed that knowledge, as well as the availability of tools.

[384] These actions correspond to the activity of *situation analysis* as first step in the superior activitiy *problem containment.* Equally to section 6.3.1.1, problem containment and all subsequently outlined problem solving steps are described according to their incorporated problem solving steps.

Next, the contents of the system of objectives are analysed and evaluated with respect to the contents of the past, e.g. how trends or competitors have developed, and future contents, e.g. which information is given about competitors´ future cars and their characteristics. Linkages between elements are identified and their validity is verified (e.g. validity of an information regarding a potential new SUV of BMW, Figure 6-14). In this activity, the contents of the system of objectives are concretised.

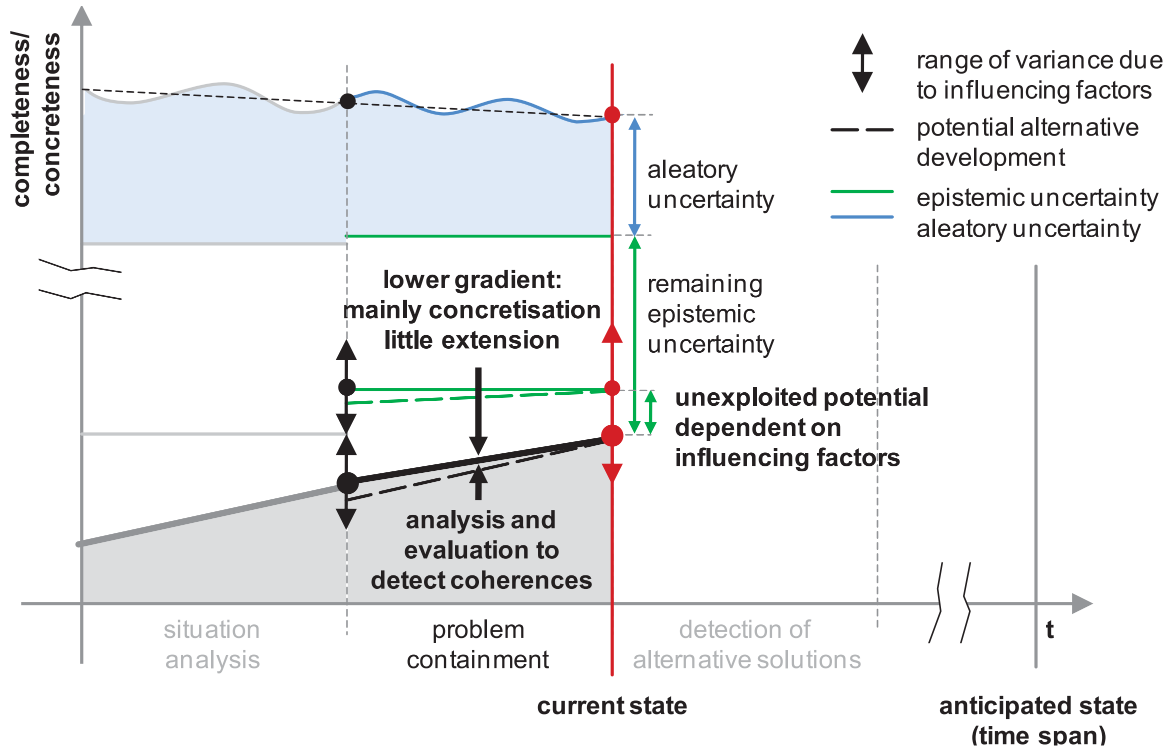


Figure 6-13: Development of system of objectives during *analysis/evaluation of coherences*

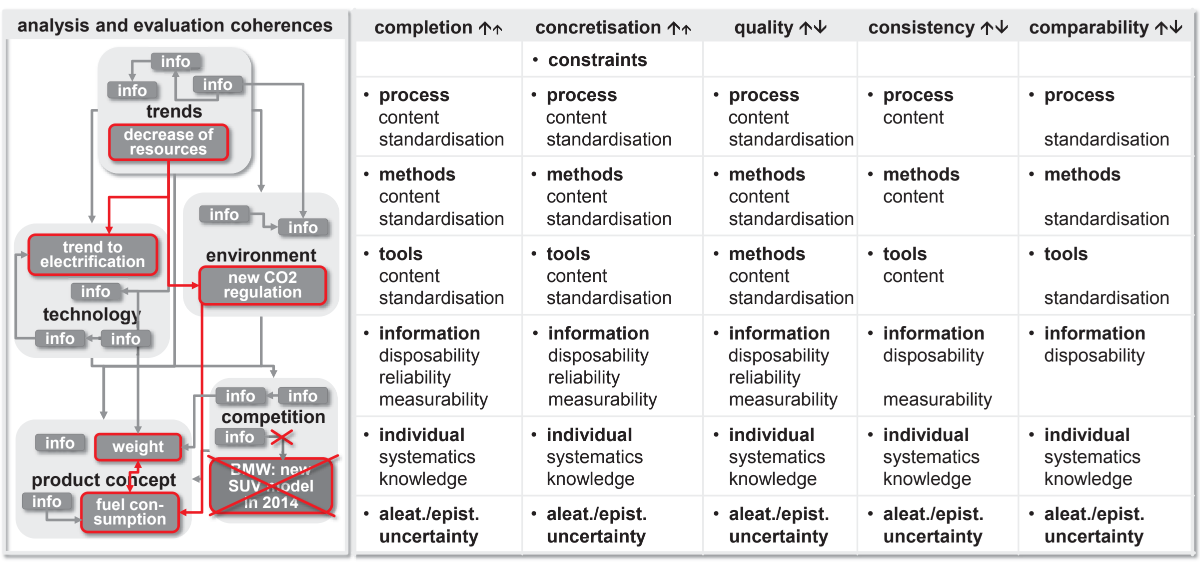


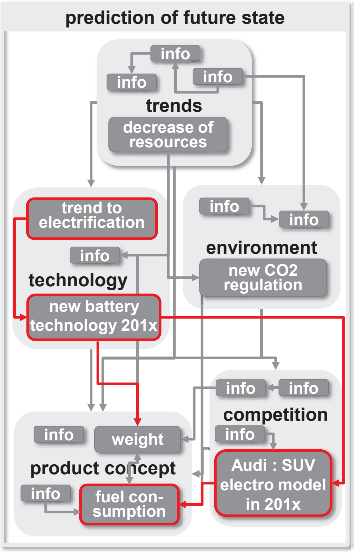
Figure 6-14: Influences on development during activity *analysis /evaluation of coherences*

This is done by identifying and defining relationships and evaluating present elements (Figure 6-14). The results depend on the steps taken as well as on the methods and tools used. This can be due to the content of a specific method e.g. *brainstorming* might suit better to identify relationships than the method *pairwise comparison* for a specific project. Due to its degree of standardisation, the method itself might also limit the field of view and thus the degree of achievable completion for this activity. The characteristics of the elements influence the possible degree of concretisation. If several engineers work on one analysis, the availability of information elements is of particular importance to how these can be evaluated in their overall context and regarding their relationships. This depends on how much of the analysis takes place in the minds of the individuals or is made more explict.

Availability of information, knowledge and people also greatly influences the consistency of the system. The reliability of individuals´ assumptions during the analysis and correct evaluation of information influence the system´s validity. The derivation of assumptions is facilitated by an increased measurability of information.

6.3.1.3 Detection of Alternative Solutions – Prognosis

The analysis of information in the system of objectives served to limit the problem to be solved in the assigned task and to identify important information and relationships relevant for the future product. This information and knowledge needs to be projected into the future to anticipate relevant constraints and influences in their future state as a basis for the derivation of objectives. As with previous activities, at first the scope of the activity is limited. The general scope is consciously or unconsciously adapted or not considered. By analysing the current state of the system of objectives, the extent to which existing information already depicts the future state on a valid basis is evaluated, this being primarily dependent on the previously integrated information and its relationships. An essential requirement for the ongoing validity of the contents is the identification and choice for a specific procedure, method or tool to be used for the prediction. During the execution of the prognosis, existing elements and relationships are combined to allow the derivation of assumptions regarding future developments and thus to derive new elements (Figure 6-15). Besides future constraints, new elements can also include new objectives which did not exist in the initial system of objectives, such as new objectives regarding electric cars (e.g. cruising range). Different methods may be used, e.g. linear forward projection on the basis of trends, definition of scenarios, or simple estimation of future state, produce results with differing validity. Methods depicting different "futures" achieve a more transparent depiction of potential alternatives and their associated uncertainty.



completion ↑↑	concretisation ↑↑	quality ↑↓	consistency ↑↓	comparability ↑↓
• constraints	• constraints			
• **process** content standardisation	• **process** content standardisation	• **process** content standardisation	• **process** content standardisation	• **process** standardisation
• **methods** content standardisation	• **methods** content standardisation	• **methods** content standardisation	• **methods** content standardisation	• **methods** standardisation
• **tools** content standardisation	• **tools** content standardisation	• **methods** content standardisation	• **tools** content standardisation	• **tools** standardisation
• **information** disposability reliability measurability	• **information** disposability reliability measurability	• **information** disposability reliability measurability	• **information** disposability measurability	• **information** disposability
• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge
• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**

Figure 6-15: Influences on the development during activity *prediction of future state*

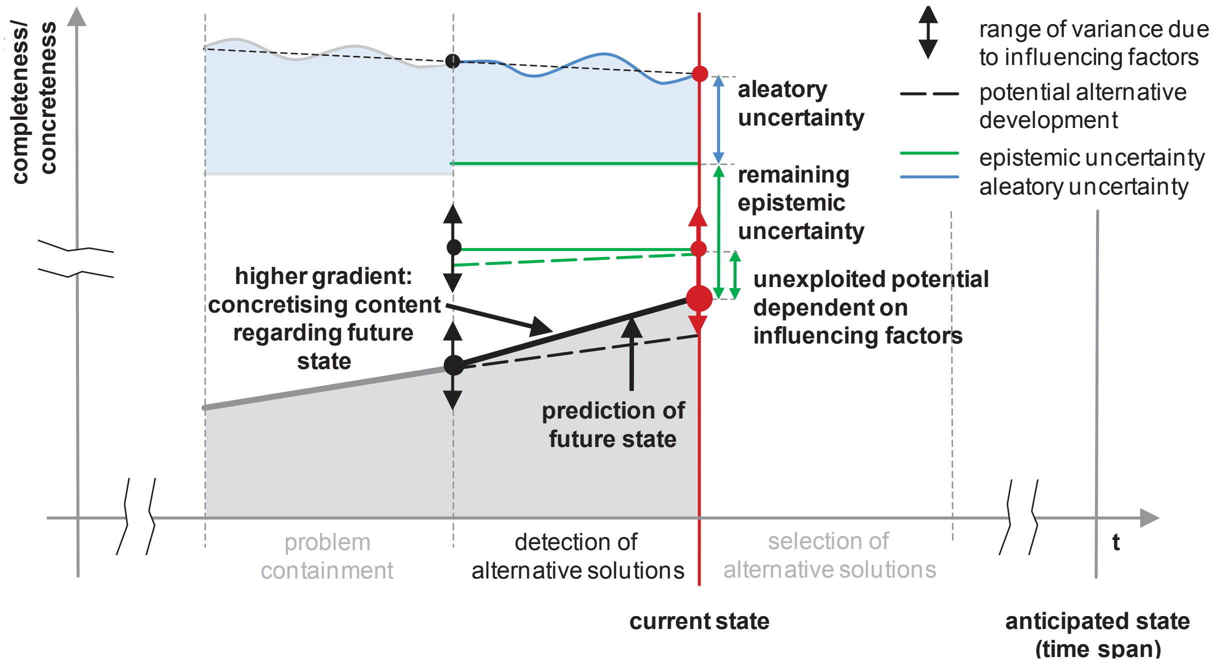


Figure 6-16: Development of system of objectives during activity *prediction of future state*

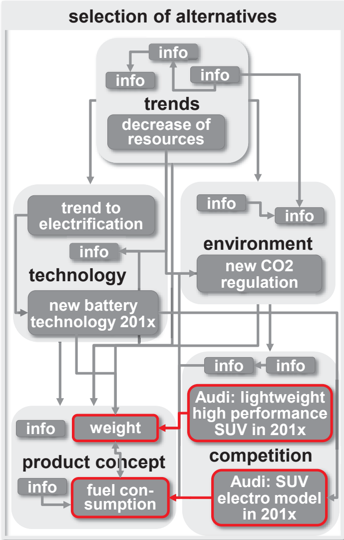
An example for a potential prognosis could be that due to given ecologic conditions and new regulations, investments in new battery technologies will increase. Thus, batteries with sufficient performance data will be available by 201x (Figure 6-14). As a consequence and due to their previous strategy, competitor xy will launch a new electric vehicle by 201x using this technology. The basic argumentation to the prognosis and the validity of elements and relationships is essential in this case. Validity, consistency and comparability of results, in particular, depend on the share of used prior knowledge or systematic procedures. Systematic procedures often produce results, which are in content terms more specific, e.g. by systematic quantification of technological influences.

The quality of the prognosis further depends on the measurability of elements. A important influence is the availability of information already incorporated in the system of objectives and needed for the prediction and its impact on consistency and completeness of the prognosis. Prognoses are more or less consciously evaluated regarding the activity’s scope. In Figure 6-16, the activity *prediction of future state* (*detection of alternative solutions*) is compared to the previous activity *analysis of information* (*problem containment*) with regard to their potential to reduce uncertainty in the system of objectives. Activities concerned with prognoses increase a system´s concreteness more than activities analysing the system, since their contents are combined and focussed on the future point in time to anticipate the future state.

6.3.1.4 Selection of Solutions – Evaluation

This activity is conducted if there are several results, from which one needs to be selected as the best. Different results need to be compared and evaluated using adequate criteria. In the generation of objectives this activity is required if prognoses are to be assessed and selected with regard to their probability of occurrence and/or (conflicting) objectives need to be prioritised. As with previous activities, this activity involves a review of the overall scope of the task and of the activity (Figure A-5).[385] This is done by regarding available alternative predictions i.e. the current state of the system of objectives and defining the aim of this activitiy. Appropriate procedures, methods and tools are identified and selected to assess the state of the system with regard to its consistency and validity. Such evaluations will depend on the availability of information contained in the system of objectives, especially in cross-departmental tasks. The choice of methods and tools is crucial within this activity to be able to identify incomparable i.e. inconsistent information elements and to evaluate their validity. If tools are applied to identify dependencies between objectives, i.e. constraints, such as a suitable calculation tool, then less prior knowledge is necessary. Tools not able to adapt to dynamic constraints may lead to distortions in results since new or modified dependencies might not be identified. An individual´s prior knowledge becomes relevant for selecting the final priorisation i.e. the alternative. Regarding Figure 6-17, a potential selection could be between a prognosis proposing the launch of a lightweight high performance vehicle by a specific competitor or the forecasting for an electro vehicle for the same competitor, both having different significance for objectives. The activity *evaluation* does not extend the elements in the system of objectives, but concretises its overall statement as regards to constraints, priorisation of objectives and likeliness of predictions.

[385] Due to little additional information conveyed for remaining problem solving steps, further figures on the development of the system of objectives (equal to Figure 6-16) can be found in appendix A.1.4.

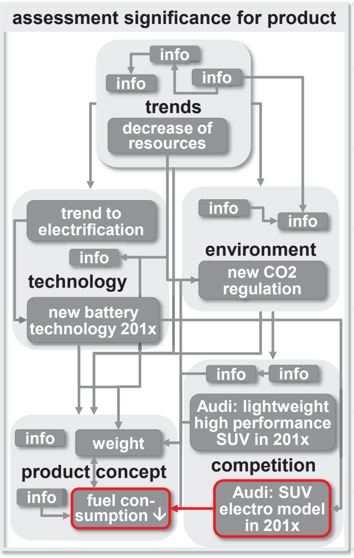


completion ↑↑	concretisation ↑↑	quality ↑↓	consistency ↑↓	comparability ↑↓
• **constraints**	• **constraints**			
• **process** content standardisation	• **process** content standardisation	• **process** content standardisation	• **process** content standardisation	• **process** standardisation
• **methods** content standardisation	• **methods** content standardisation	• **methods** content standardisation	• **methods** content standardisation	• **methods** standardisation
• **tools** content standardisation	• **tools** content standardisation	• **methods** content standardisation	• **tools** content standardisation	• **tools** standardisation
• **information** disposability reliability measurability	• **information** disposability reliability measurability	• **information** disposability reliability measurability	• **information** disposability measurability	• **information** disposability
• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge
• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**

Figure 6-17: Influences on the development during activity *selection of alternatives*

6.3.1.5 Analysis of Consequences – Assessment of significance for product

The selected alternative needs to be evaluated regarding its effects on the actual product to be developed. This means that the contents of the system of objectives need to be assessed regarding potential changes and risks in respect to the future product as a basis for a succeeding product related decision. In a similar way to the previously described activities, the scope of the superior task and for the specific activity is reviewed first (Figure A-6). Results from previous activities are then analysed and the content, which needs to be evaluated regarding potential changes and risks, is identified. The evaluation and choice of procedures, methods and tool for this activitiy is largely dependent on the individual. Procedures used by different individuals vary in their extent, for instance in how consistently identified constraints are evaluated regarding their effect on technical objectives, i.e. how they might change until the product enters the market and what risks and changes such a change might evoke. An example might be to find out what effects the launch of a specific car model from a competitor might have on their own objectives, i.e. what a potential shift in the competitors strategy would mean for their own objectives (range of potential competitive operations). Thus, information in the system of objectives needs to be evaluated with regard to its truth. If necessary, new information elements need to be integrated, i.e. existing elements need to be modified. Apart from that, the system is mainly concretised by deriving concrete recommendations for action. The degree is dependent on the measurability of the elements in the system. The identification and articulation of remaining uncertainty in the system of objectives is an important factor for supporting product relevant decisions. This identification and description is particularly dependent on prior knowledge regarding the product, the estimation of the overall scope and remaining epistemic uncertainty. Results are usually documented for decision situations.



completion ↑↑	concretisation ↑↑	quality ↑↓	consistency ↑↓	comparability ↑↓
• **constraints**	• **constraints**	• **constraints**	• **constraints**	
• **process** content standardisation	• **process** content standardisation	• **process** content standardisation	• **process** content standardisation	• **process** standardisation
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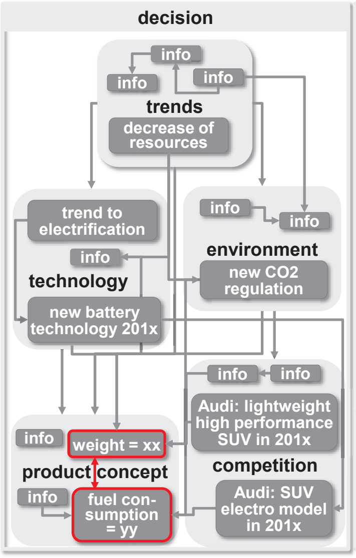
• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**

Figure 6-18: Influences on the development during activity *assessment of significance*

6.3.1.6 Decision and Implementation

Preceding activities have served to gather information, integrate it into the system of objectives and concretise incorporated elements. The actual fixing, i.e. definition, of a certain state of the system of objectives requires an explicit decision. On the basis of previous insights, objectives and constraints regarded as relevant are finally identified and implemented into the process. Such decisions are often not made by the same individuals who previously had a share in generating constraints or objectives. Thus, the overall scope may vary (Figure A-7). At first, the decision to be made is analysed, i.e. which objectives are in focus, what is the relevant context and what importance does the decision have for the actual product engineering process. Procedures for elaborating a decision are often intuitive, methods and tools are seldom actively used.

The decision finally fixes which constraints are regarded as relevant to the product, i.e. which elements in the system of objectives are, as technical objectives, relevant to the product to be developed. This decision is of particular importance to the subsequent course of a project. It depends on the prior knowledge of the decision maker, their procedures and informational basis, i.e. which information is used and how valid this information is. In this step, the system of objectives is concretised with regard to elements determined to be relevant as objectives, describing these and their consequences for the successive engineering process (Figure 6-19).



completion ↑↑	concretisation ↑↑	quality ↑↓	consistency ↑↓	comparability ↑↓
• **constraints**	• **constraints**	• **constraints**	• **constraints**	
• **process** content standardisation	• **process** content standardisation	• **process** content standardisation	• **process** content standardisation	• **process** standardisation
• **methods** content standardisation	• **methods** content standardisation	• **methods** content standardisation	• **methods** content standardisation	• **methods** standardisation
• **tools** content standardisation	• **tools** content standardisation	• **methods** content standardisation	• **tools** content standardisation	• **tools** standardisation
• **information** disposability	• **information** disposability reliability measurability	• **information** disposability reliability measurability	• **information** disposability measurability	• **information** disposability
• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge
• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**

Figure 6-19: Influences on the development during activity *decision*

6.3.1.7 Recapitulation and Learning

This activity is conducted if the state of the system of objectives needs to be assessed with regard to its fulfilment of the initially defined scope. This activity is undertaken to check whether enough information was collected and whether this information is concrete enough to fulfil the initially defined task or if changed constraints may require the execution of such activities to be repeated.

In addition, information from previous activities is to be made available for those individuals and departments concerned with the further elaboration of the product. After setting the scope for this activitiy, the results from previous activities are compared to the initial overall scope (Figure A-8). Potential changes in constraints are identified. It is also decided which procedures, methods and tools are used to make results available for the organisation. The extent to which information is identified as important and provided for a subsequent project is essential for the associated initial system of objectives. This depends particularly on the availability of information, existing assumptions made by the company and available methods and tools (Figure A-9).[386] The content of the system of objectives may be extended and concretised by this activitiy. Necessary iterations might cause a further refinement of the overall system.

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[386] Due to little added value for understanding this activity, the figure can be found in appendix A.1.4.

6.3.2 Product Engineering Activities

To get a full picture of the generation of objectives, not only the distinct problem solving activities and their influence on the development, but also the embedding of these activities in the actual product engineering process needs to be looked at.

The main task of the system of objectives is to provide the essential input to product relevant decisions at the right point in time in the engineering process. Thus, the specific state of the system needs to suit the decision to be made, i.e. needs to be ensured before the respective decision. Referring to section 6.1.2, such decisions may have two characteristic forms: either they serve to validate the objectives themselves or they serve to validate the product to be developed. If it is presupposed that the product engineering activities are always targeted towards developing the “right thing right,” then decisions regarding the validity of objectives need to be made *before* the validity of a product concept can be assessed and even before the position of a product concept in its environment can be evaluated (Figure 6-20, ❶). Otherwise, an alignment of the entire product concept to future demands cannot be ensured. Subsequently, a concretisation and completion of this system of objectives, comprising mainly high-level objectives, to a state in which detailed judgments regarding the product itself can be made needs to happen before the product concept is finalised (❷). To optimise the support of such decisions in the engineering process by using the system of objectives, its degree of concretisation, completion and its quality need to be as high as is appropriate for the specific decision situation (Figure 6-20). If these arguments and insights from previous sections are applied to Figure 6-6 and Figure 6-8, it becomes obvious that the development of systems of objectives cannot proceed linearly. Diagrams derived in the past section described the share each of these activities has on reducing uncertainty.

It was shown that they differ with respect to the amount of uncertainty they typically reduce (e.g. section 6.3.1.3, line gradient). If the lines with different gradients from successive activities are aligned and are regarded from a holistic perspective, a curve results. If these insights are projected onto an entire product engineering process, three characteristically different stages in the development of such a curve can be observed (exemplary visualisation, Figure 6-20). The first covers the generation of objectives based on the relevant constraints and their validation (❶). The second stage comprises the concretisation of objectives to allow validation of the product concept (❷). The third stage depicts the monitoring of the system of objectives in successive activities (❸). The first two stages are characterised by a high curve gradient. In the first stage this gradient results from the high level of integrated and specified information and knowledge required to generate objectives. In the second stage, the system is extended and concretised by detailing given objectives in response to the growing knowledge about the product.

The third stage has a low gradient, since it responds to changing objectives only if key constraints change due to resulting effort and costs. The curve is not to be seen as a rigid sequence of activities, since changes in constraints or influencing factors might cause iterations or use of different procedures. Thus, the development of a system of objectives is always unique. The previous section has shown that changes in state and quality of systems of objectives can be depicted by problem solving activities. Thus, the overall development of a system of objectives (Figure 6-20) can be understood as the accumulation of distinct problem solving processes of the various contributing individuals on different levels of abstraction.

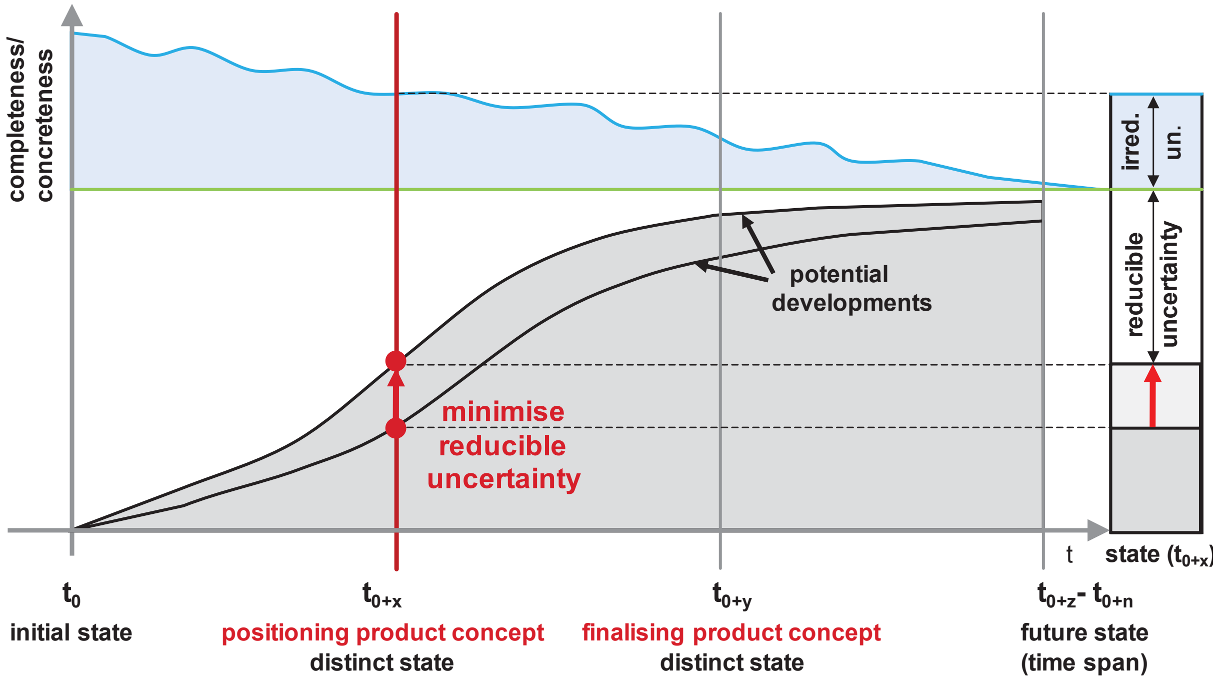

Figure 6-20: Development of systems of objectives throughout the engineering process

This holds for all three stages identified. Thus, stages can be differentiated by their different focus, as explained, but all can be decomposed and described by activities from problem solving processes. The ideas of this section are supported by insights from section 5.2, which revealed that the development of objectives cannot be strictly matched with stages in an engineering process, as well as by the evaluation of several past engineering projects at Porsche AG and an illustration of the average deviation of objective values from their final state (Figure 6-1).

6.3.3 Insights

The previous sections investigated the development of objectives to build a theory describing how objectives are in practice generated, how constraints are considered and how factors, as summarised in section 5.5, influence these activities. Three main insights regarding the development of objectives could be derived.

Definition 6-10: Activities in the Development of Systems of Objectives

Activities contributing to the development of objectives resemble the fractal micro activities of problem solving. Hence, the overall process to develop objectives is a superposition of various problem solving processes of the contributing individuals. The sequence of activities and thus the process is unique. The actual modification of the system of objectives is supported by explicit or implicit decisions (micro activitiy *decide and implement*).

Definition 6-11: Modification of Uncertainty

The development of systems of objectives can be understood as a modification of the uncertainty in the system. The degree of the modification depends on the characteristics of the prevailing influencing factors.

Definition 6-12: Influencing Factors

Influencing factors can be amenable or irreversible. Through a controlled manipulation of the amenable factors, uncertainty in the system of objectives can be actively reduced. Strategies to handle the development of objectives need to consider this basic characteristic of influencing factors.

In reality, all the steps of the problem solving cycle are always conducted, but more or less consciously by the individuals responsible for them. The achievement of results is often not controlled, leading to iterations. Of particular importance to the development of the system of objectives is the step of *decision and implementation*, in which the actual extension and concretisation, thus the change of the state of the system of objectives, is accomplished. Previous and successive steps do not directly modify the system of objectives, but are essential for reducing the degree of uncertainty (see next section). Changes in the state of the system result from changes in the attributes of its elements. The state of an attribute depends on how the corresponding element was integrated and elaborated. Empirical studies have shown that there is a tendency in systems of objectives for information elements to be developed from being rather qualitative to quantitative, from project independent to project dependent, from overall to a limited validity and from long term to short term scope during a project.

The development of the system of objectives can be described by the development of its associated uncertainty and impact of influences. Some of the influencing factors are themselves not amenable, such as constraints and their dynamic character, represented by the system´s aleatory uncertainty (Table 6-9, red). With other factors, such as activities undertaken, methods and tools used, as well as processed information, the processing individual and epistemic uncertainty are amenable (Table 6-9, green).

Thus, reducing epistemic uncertainty represents the key to achieving an improved state of system of objectives with increased quality earlier in the process. The degree of reduction depends on the influencing factors, while their influence on epistemic uncertainty is present if recognised or ignored. Uncertainty, constraints and the individual always influence the development. Since uncertainty is always subjectively judged, systems of objectives can *never* be objectively complete or concrete.

Table 6-9: Effects of influencing factors on state and quality of the system of objectives

factor		completion	concretisation	validity	consistency	comparability
	constraints	set necessary scope, elements, relations.	set necessary scope and content	set necessary validity	set necessary consistency	set necessary comparability
un-certainty	aleatory	unexpected changes in constraints/factors	unexpected changes in constraints/factors	unexpected changes in constraints/factors	unexpected changes in constraints/factors	unexpected changes in constraints/factors
	epistemic	lack of knowledge	lack of knowledge	lack of knowledge	lack of knowledge	lack of knowledge
process activity	content	↑↑	↑↑	↑↓	↑↓	
	standardisation	↑↑	↑↑	↑↓	↑↓	↑↓
meth-ods	content	↑↑	↑↑	↑↓	↑↑	
	standardisation	↑↑	↑↑	↑↓	↑↓	↑↓
tools	content	↑↑	↑↑	↑↓	↑↓	
	standardisation	↑↑	↑↑	↑↓	↑↓	↑↓
information	availability	↑↑	↑↑	↑↓	↑↓	↑↓
	reliability			↑↓	↑↓	↑↓
	measurability		↑↑	↑↓	↑↓	↑↓
indi-vidual	systematics	↑↑	↑↑	↑↓	↑↓	↑↓
	prior knowledge	↑↑	↑↑	↑↓	↑↓	↑↓

6.4 Strategies to Handle the Development of Systems of Objectives

After studying the generation of objectives and influences on this process, the next section uses these insights to address the second part of the initially stated problem.

First, a basic model is introduced to depict the development of objectives and relevant influences, then strategies are proposed to overcome deficiencies identified and to make this process accessible for use in operative management and improvement.

6.4.1 Model of Influences

Influences on the generation of a system of objectives are summarised in a model of influences (Figure 6-21) which is based on the following definition:

> **Definition 6-13: Model of Influences on the System of Objectives**
> Since a system of objectives is an abstract model of a future reality, its development can be described as a transformation of currently available implicit and explicit information and knowledge to provide a model of a future reality in order to make this reality accessible to the current engineering activities. The model´s state and quality depend on the implicit and explicit models used.

A model of a system of objectives comprises implicit and explicit information and knowledge which is assumed to be relevant for a specific decision situation and a specific individual. The actual utility of the model for a specific decision situation is dependent on its adequacy with regard to completeness, concreteness and quality. The transformation and integration of available information and knowledge into the model happens by undertaking activities from the problem solving process. Figure 6-21 depicts the transformation process for *one* activitiy.

In each activity, an individual perceives a certain extract of reality as task relevant. This has been called *scope* in the previous sections. What lies inside the scope and which information, knowledge and interrelationships are perceived as relevant depends on an individual´s prior knowledge, experiences, and how systematically they proceed to define the scope and to detect information as well as on the properties of the information itself (availability, measurability, reliability).

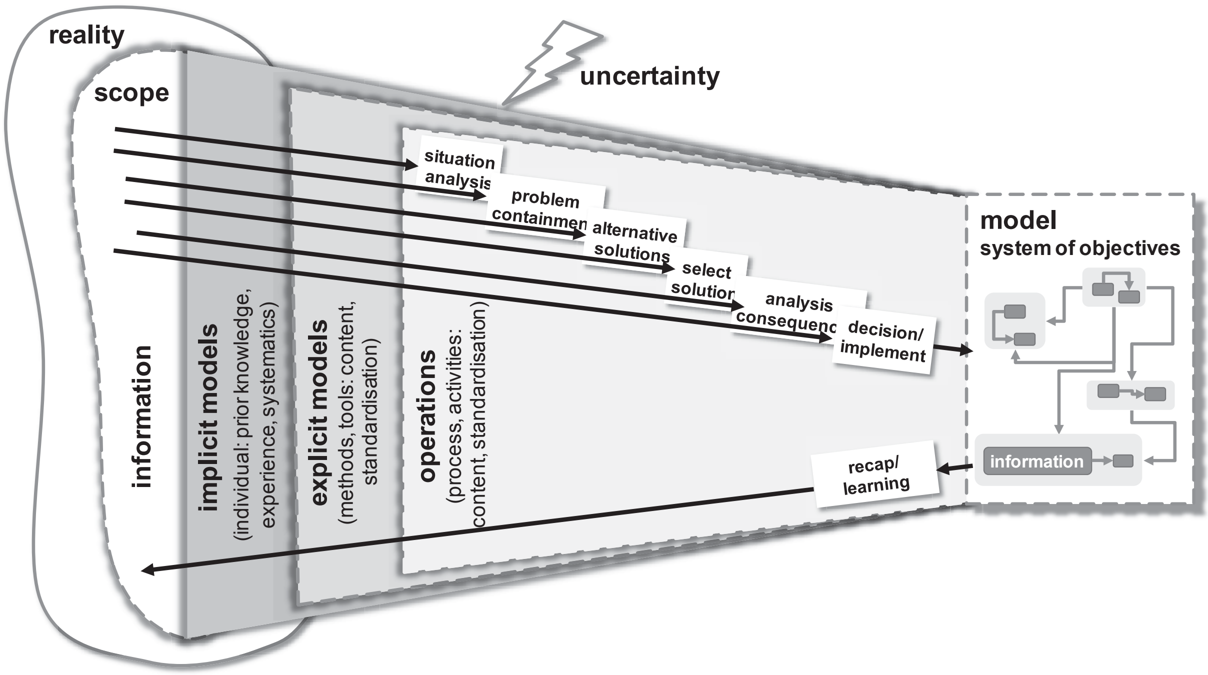

Figure 6-21: Interlinked influences in the development of objectives

Thus, implicit models of an individual function as a filter, tailoring the given reality. How well this description of reality suits the given task influences the state and quality of the developed system of objectives. The degree of influence depends on the characteristics of the implicit models of each individual. Depending on if and which explicit methods and tools were chosen for the conduction of an activity, the perceived information, knowledge and relationships relevant to the system of objectives are further tailored according to the explicit models underlying the method or tool. An example may be a tool which is only able to depict a certain number of dependencies between a fixed set of parameters, such as is often the case in databases. The suitability of these explicit models thus influences the number, concreteness and quality of elements integrated into the model of the system of objectives. The actual operation is then conducted by the individual, based on the extract of reality filtered by the explicit and implicit models used. The actual building, i.e. the integration and linking of information and knowledge in the model of the system of objectives, happens through an explicit decision and subsequent implementation by the individual. This filtering process describes the coherence between distinct factors and their eventual influence on the resulting model of the system of objectives.

6.4.2 Strategies for Handling the Development of Systems of Objectives

Chapter 5 revealed that since there is no uniform idea or explicit description of an actual *process*, including methods and tools, for the generation of objectives and no explicit overview exists of constraints handled, objectives and their coherence, activities and their outcome cannot be actively managed and improved. This chapter disclosed the potential to improve the generation of objectives by actively handling the reduction of uncertainty. This can be achieved by manipulating amenable influencing factors to reduce uncertainty, while accounting for irreversible influencing factors, by designing a standardised approach to supporting the process which is able to react flexibly to potential changes. These findings motivate the strategies formulated in the next sections to access and improve the generation of objectives.

6.4.2.1 Articulation of Process Elements

To make the generation of objectives accessible for use in operative management and improvement, it is first of all necessary to make those activities explicit, as well as methods and tools, objectives handled, associated constraints and their relationships that contribute to the process.[387]

[387] The term *process* is used to facilitate a reference to the operational embedding of the generation of objectives, i.e. contributing elements. It shall explicitly *not* indicate a fixed sequence of activities.

This can be done by analysing past projects and monitoring current projects with regard to activities, methods and tools that had a share in generating constraints and objectives. In addition, objectives developed, constraints assumed and their relationships can be identified. This requires a holistic perspective, integrating all departments and individuals who contributed to the process. The results may be adapted to take into account the constraints relevant to a current, specific project for which process elements need to be identified.

6.4.2.2 Identification of Uncertainty

If the elements contributing to the process are known, the process can be assessed regarding potential uncertainty factors. Since the effects of influencing factors may vary from project to project, the prevailing sources and type of uncertainty need to be identified before being able to define an appropriate strategy to handle uncertainty.[388] According to section 3.1.4.2, existing uncertainty can be classified regarding its underlying *character*, *degree*, *source* and *effect*. Each influencing factor represents a potential source of uncertainty. Aleatory uncertainty exists in the dynamic character of observed constraints, in associated information, i.e. its properties, and unforeseeable events in all other influencing factors (e.g. sudden illness of an experienced employee). Epistemic uncertainty through a lack of knowledge can result from insufficient prior knowledge of the individual conducting an activity (implicit) or from the use of methods and tools that do not provide the information required (explicit), e.g. incomplete databases. Uncertainty, through a lack of description can emerge from incomplete implicit and explicit models used for identifying scope and necessary contents of a system of objectives (see previous section). Uncertainty in articulated constraints can be further specified for single constraints, based on the knowledge from previous projects through, for example, evaluating the validity of information from the sources used (e.g. did a prognosis for a certain technologic development come true?). The effect of uncertainty on the development of the system of objectives can be assessed by evaluating its relative effect on the concretisation, completion and quality (e.g. if the effect of a technologic development on an objective is not quantified, this lowers the quality of the objective). An evaluation of the resulting risk can be made using the criteria from SMETS (Table A-2), e.g. by assessing a technologic trend with regard to the likelihood that it is wrong or that its source is believable. The identification of the predominant uncertainty within a system of objectives is always subjective and can only be made on a relative basis, e.g. by using knowledge from past projects.

[388] see also Chalupnik et al. 2009

As stated in section 3.1.4.4, due to limited knowledge on the product to be developed, complex stochastic approaches for assessing uncertainty in the early project stages are not applicable and pragmatic strategies are necessary. In order to minimise uncertainty, as much uncertainty as possible should be identified and be defined as epistemic.

6.4.2.3 Reduction of Uncertainty

The following paragraphs outline some basic principles which can be adopted to reduce uncertainty during the generation of objectives. Due to the scope of this work, specific methods and tools are not described in detail.[389]

Aleatory uncertainty cannot be resolved as such, but converting as many *unknown unknowns* into *known unknowns* as possible will help to expand the field of epistemic uncertainty to be as wide as possible. This applies to all potential sources of uncertainty. The articulation of process elements, as previously described, serves as a first step. The evaluation of similar products or previous product generations already on the market may reveal important insights with regard to which of the anticipated constraints came true or which main constraints had been ignored or neglected (section 6.1.1). Constraints made explicit prior to a project may reduce initial uncertainty in a system of objectives (section 6.3.1.2).

The content of articulated process elements may be evaluated to identify those with a positive effect on the state and quality of the system of objectives. For activities, this can be done by evaluating past projects concerning the activities undertaken and results achieved. Sequences of activities and their associated procedures and tools, contributing individuals and information processed, all of which led to (intermediate) results with high validity, consistency and comparability should be identified. Similarly, methods that were effective in reducing uncertainty and in improving the concretisation and completion of the system of objectives, while supporting its quality, should be identified from past projects. In addition, new methodological approaches may be evaluated regarding their suitability for a given project context. In doing so, it is useful to follow the principle “it is better to be approximately right than to be precisely wrong.”[390]

[389] The principles base on the findings from the state of the art. For further detail on specific methods and tools, it is referred to literature as listed in the specific sections in Chapter 3.

[390] cp. to Hubbard 2007, citing Warren Buffet

When evaluating new methods and methods currently in use, the following principles shall be considered:

- support transparency to identify relationships between elements and avoid errors and invalid assumptions during the derivation of results (↑ validity and consistency)
- improve future predictions by implementing scenarios instead of single point predictions (↑ validity (reliability))
- interlink methods in the process, synchronise (intermediate) results to obtain coherence in the overall argumentation (↑ consistency and comparability)

Past projects may also provide insights with regard to the tool functionality required. Tools are best suited to the reduction of uncertainty if they support the execution of activities and methods which have previously been identified as important for the reduction of uncertainty. Furthermore, tools need to support the availability, reliability and measurability of information. The following principles may be considered:

- increase the validity of assumptions by supporting the workflow of activities and thus the articulation of knowledge (↑ quality, consistency, comparability)
- support the articulation of elements and relationships (↑ support consistency)
- provide suitable data structures to enable the description and storage of a wide range of elements and relationships (↑ concretisation and completion)

Uncertainty caused by the information and knowledge handled in the process may be reduced by taking into account the following principles:

- enable *availability* by supporting the articulation of information and knowledge and by providing suitable tools (↑ completeness, consistency)
- improve *reliability* through the thorough evaluation and review of sources, articulation and reconciliation of intermediate results and by increasing information availability and highlighting residual uncertainty in decision situations (↑ validity)
- improve *measurability* by decreasing fuzziness and ambiguity, and by supporting quantification in the methods and tools used (↑ validity)

Uncertainty emerging from unsystematic procedures used by an individual can be limited by the provision of a suitable framework of activities, methods and tools. Reconciliation in teams at defined points in time should be enforced, as well as the standardisation of expressions and their associated application to the process and its elements. Prior knowledge can be increased by sharing of knowledge between contributing individuals and by improving the availability of knowledge from prior projects.

6.4.2.4 Design Flexible Support

An essential condition to improve access to the generation of objectives is to provide support for the description and management of process elements. To fully exploit the potential of the influencing factors to reduce uncertainty, this support needs to ensure the best possible degree of standardisation in the process, while being able to adapt flexibly to changes arising from aleatory uncertainty, such as changes in constraints. Since the overall process of the development of objectives is composed of the various different problem solving processes of contributing individuals (section 6.3.3), an approach to support the overall process needs to be scalable to different levels of abstraction.

Process elements that might be standardised can be identified and provided by:

- *identification*: of project independent, content related *clusters* and *elements* of a system of objectives e.g. ecologic trends (cluster), trends towards a decrease of resources (constraint), *activities* (resources, (intermediate) results, sequences) collection of information, *methods* e.g. scenarios, *tools* e.g. database
- *reconciliation* between elements of the system of objectives, activities, methods and tools, identified to be important for reducing uncertainty (section 6.4.2.3)
- *unification*: define a common language and uniform understanding to describe elements of the system of objectives, activities, methods and tools

These resulting elements of the system of objectives, activities, methods and tools form the backbone for each project. They need to be specified and complemented before and during each project regarding specific and changing process constraints.

6.4.3 Insights

This section has presented a model which comprises the findings of previous chapters to describe the coherence of specific influencing factors and their effects on the generation of a system of objectives. On this basis, strategies were suggested to make the generation of objectives accessible to improvement. These propose the articulation of process elements, a reduction of uncertainty by actively modifying influencing factors and the provision of standardised, but flexible, modelling and management support.

6.5 Implications for the Modelling Approach

Based on the idea to assess objectives and their associated constraints as part of a holisitic system, this chapter developed a common understanding of the elements of this system and their relationships. It was found that activities contributing to the generation of systems of objectives resemble (abstracted) problem solving steps. Furthermore, it was revealed that systems of objectives develop characteristically depending on the respective prevailing activity of the product engineering process.

The development of a system of objectives can be described as the reduction of the uncertainty associated with prevailing influencing factors. Strategies were proposed which suggest using amenable factors to actively manipulate and improve the reduction of uncertainty. To be able to articulate and thus make the system of objectives and its influencing factors accessible to handling and management, flexible support of the process is required which can provide a standardised structure, adaptable to specific project constraints and various levels of abstraction. Thus, a modelling framework is needed which is able to describe the elements and relationships of the system of objectives, as identified in section 6.2, and the activities which contribute to its generation and to ensure that the objectives are accessible for improvement. This framework needs to be able to derive reference processes for process modelling and management which can be adapted according to the changing constraints in projects and be updated for new projects.

7 Modelling the Development of Systems of Objectives

The previous chapter has shown that the development of a system of objectives describes the transformation of an anticipated reality into a partly implicit and partly explicit model. This model serves as decision support to validate not only the objectives, but also the product to be developed. During this transformation, the different elements of the system, objectives and constraints, as well as their relationships migrate across different degrees of concretisation. The transformation process itself is triggered in part by implicit activities on varying levels of abstraction and influenced by various factors. These conditions demand a modelling framework,

- scalable to different levels of abstraction.
- supporting the articulation of implicit elements and relationships within the system of objectives as well as with associated activities.
- adaptable to changing constraints, but also provides a standardised structure.

This section addresses the second part of the initial problem, namely the fourth research question; how to improve the generation of objectives with consideration of the relevant constraints. It gives a brief review of the literature on abstraction, in the context of modelling, and adapts insights to the systemic approach of iPeM (which had been chosen as suitable basic modelling framework for this research work). The representation of the system of objectives as well as of the operation system in iPeM is extended adopting principles of systems and an enhanced concept of abstraction levels within the modelling framework. The two representations are fused to provide a general modelling approach to describe the development of systems of objectives.

7.1 Modelling on Different Levels of Abstraction

The term *model* is used in all sorts of contexts to describe the abstraction of a complex reality into an accessible representation. However, often it is not even obvious to individuals that they are making use of a model in a given situation.[391]

To provide a basis for the following reflections, the main characteristics of a model are summarised. A model is always a representation of an original. The act of abstraction from reality is based on an intention and this intentional abstraction is in parallel a *generalisation.* STACHOWIAK lists three main characteristics of models:[392]

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[391] cp. to Hubka & Eder 1996, p. 117
[392] cp. to Stachowiak 1973, pp. 131

- *description*: As representations or descriptions of natural or artificial originals, models are always modelling something. Originals can themselves be models.
- *contraction:* Not all attributes of the original represented are captured by a model, but only those seeming relevant for the creators or users of the model.
- *pragmatic*: There is no direct assignment of models to their originals. To be fully determined, the notion of a model needs to be put into a pragmatic perspective. Models are for someone human or artificial (machine) to fulfil functions during a certain interval of time and are brought into existence for a certain purpose.

Scientific models can be regarded as systems, since they are based on originals with characteristics of systems. This is expressed by building a unified and structured entity using relationships between elements.[393]

7.1.1 Abstraction of Reality

One insight gained from the analysis of the development of systems of objectives in the previous chapter was that the description of a future reality as a basis for each system of objectives is shaped considerably by the interpretation of the individual anticipating this reality and its underlying coherence.[394] Thus, to approach the act of modelling as the objective mapping of reproducible structures of a reality to a model, seems to be insufficient in this case, where modellers themselves solely need to be able to identify relevant elements and structures to transform them into a formal structure[395]. A modelling approach should stick to an understanding of modelling, which assumes that real structures cannot be identified independently from the subject who is detecting them. Structures are only perceived dependent on the perceiving individual.[396] STACHOWIAK contributed to this insight by formulating the *pragmatic* characteristic of models (previous section). This perspective is particularly helpful when prescriptive models, which need to be formative, are developed.[397]

This description of modelling requires the explicit consideration of the individual in the procedure of modelling. The *mental model* of each individual represents the link between the original (reality) and its formal representation in an (explicit) model. Results from the interpretation of reality are combined with previously known or newly built mental structures which contribute to the *construction* of the model.

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[393] cp. to Stachowiak 1973, pp. 137
[394] see also section on perceived uncertainty, section 3.1.5.4
[395] German = “abbildungsorientiertes Modellverständnis”,
cp. to Schütte 1998, pp. 46, Hammel et al. 1998, Berens & Delfmann 1994, pp. 24
[396] German = “konstruktionsorientiertes Modellverständnis”,
cp. to Schütte 1998, p. 49, Berens & Delfmann 1994, pp. 25
[397] cp. to Rupprecht 2002, pp.12

In particular, when potential or desired future realities are modelled, as in the case when developing a system of objectives, the construction of the model is self-evident. This is because future structures do not represent reality at the point of modelling and can as such not be perceived. They need to be anticipated on the basis of potential realities the modeller believes to be likely. By mapping the mental model to a formal model representation, a subjective assignment of attributes of the mental model to the formal representation takes place. As also found in the previous chapter, this mapping procedure includes elimination of irrelevant issues to reduce complexity. The result is an explicit model system. An assessment of the structural compliance of a mental and an explicit model system cannot be objectifiable. The transformation of reality into a mental model and subsequently into an explicit model does not proceed sequentially.[398] In a similar way, this was found with the procedure for modelling a system of objectives in which, even in critical use situations, essential parts of the model still remained implicit in individual's minds. In addition, this transformation process was found to be influenced by the methods and tools used.

7.1.2 Forms of Abstraction in Models

HARS describes the subjective interpretation of reality by an individual in defining a so called *object system (OS)* (Figure 7-1). This system represents the selected part of the real world. It is transformed by a *projection* into a *model system (MS)*, representing the subjective image of the object system. In the projection, complexity is reduced by eliminating and clustering elements with similar content. This reflects the findings about the development of a system of objectives (section 6.4.1). The *meta model system* (MM) provides basic modelling elements for building the model system (MS). If there is a model, M2, covering the model system, MS, MM and the modelling purpose, M2 is called *meta model* to the object system. HARS finds that for simplification, model system MM of the meta model is often referred to as meta model.[399] A meta model can be regarded as design framework, describing basic model elements and their relationships. It defines rules to use and specify elements and relationships. There has to be an unambiguously specified, consistent, complete relationship between elements of model system MS and meta model system MM.[400]

Besides the abstract meta model, a *reference model* is a more specific model. It serves as basic pattern for the design of more specific models. There needs to be a specified relationship between the reference model and the specified model.

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398 cp. to Rupprecht 2002, pp.15

399 cp. to Hars 1994, p. 11, this expression is adopted for this thesis

400 cp. to Rosemann & zur Muehlen 1997, p. 17, Rosemann 1996, Hars 1994, p. 11,

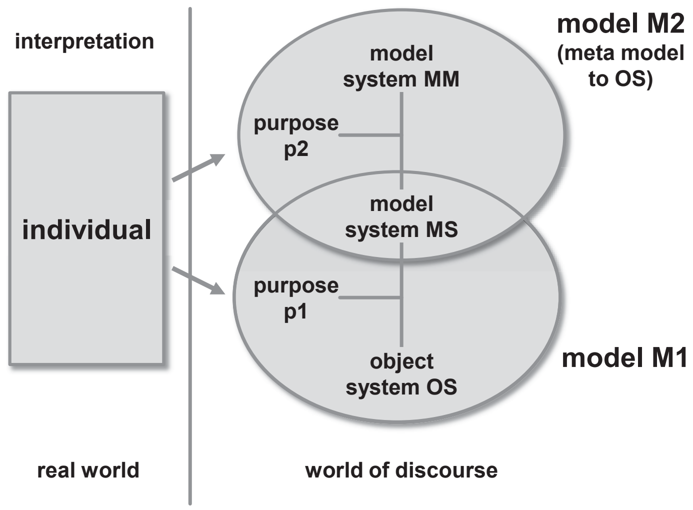

Figure 7-1: Components of a meta model[401]

This depiction needs to be useful, not consistent and complete, and to have a certain degree of generality, at least for the specification of a couple of other models. It is important to specify how the reference model may be adapted to constraints of a specific model. The aim of reference models is to reduce the effort of modelling.[402]

RUPPRECHT names the abstraction level of the reference model the *level of type.* The abstraction level of the model to be specified on the basis of the reference model is called the *level of characteristics* (Figure 7-2). Together with the abstraction level of the meta model, these levels are called *model levels*. They represent an abstraction, i.e. generalisation of the formal structure of the each model, but do not further specify the described content. He finds that process models can also be differentiated with regard to their *content related individuality*, i.e. the degree of their *generality* or level of *content related abstraction*. Basically, a multitude of different levels can be defined, but a useful classification would include

- *branch specific* models or *general procedure* model (outside companies)
- *company specific* models (generalisation of content of concrete process cases)
- *use case specific* models (adaptation to individual constraints)

The degree of individualisation depends strongly on the known constraints to a process. The more constraints, changes to constraints and their effects to a process are known, the more the model can be adapted and individualised (completeness). This results in less freedom to process changes and less application cases which can be captured by the model. Since constraints may occur or change during an entire project, the degree of individualisation may change throughout a project.

[401] Hars 1994, p. 12, see also Rosemann & zur Muehlen 1997, p. 2
[402] cp. to Hars 1994, p. 16

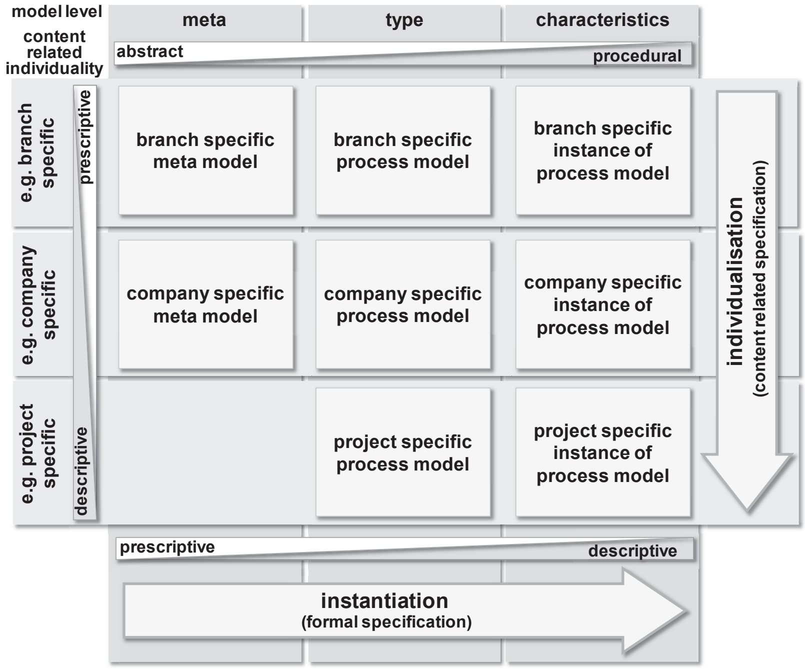

Figure 7-2: Abstraction levels and model characteristics[403]

Content related individualisation is only helpful as long it saves effort when building new models.[404] Figure 7-2 shows the matrix which emerges when the different formal and content related abstraction levels are drawn against each other. It classifies the different types of engineering models, as described in section 3.2.2.2, and shows that a holistic engineering model to describe any possible situation in an engineering project needs to accommodate different formal and content related model levels.

7.1.3 Implications

This insight into modelling fundamentals showed that modelling is to be considered as construction, dependent on subject and purpose. It revealed that the articulation of implicit contents can only be encountered by providing a modelling framework implementing a meta model as unified language. It needs to support a standardised modelling procedure to reduce uncertainty, but leave freedom to modify a model according to a modeller´s own perception of information to be modelled or during process execution. Different abstraction levels are needed to adapt a process model to changing constraints based on one holistic model. Research has addressed these insights mainly only for conventional business processes. To be used as basis for the approach of this thesis, they need to be transferred to the characteristically different product engineering processes (section 3.2.2.1). This is done with the holistic product engineering approach of iPeM to be used for the modelling approach of this thesis.

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403 based on Rupprecht 2002, p. 54, Browning et al. 2006, Wynn & Clarkson 2005
404 cp. to Rupprecht 2002, pp. 49

7.2 Abstraction Levels of iPeM

Section 3.2.3.2 introduced iPeM as an holistic modelling framework, building on four model levels, the *meta model*, *reference model*, *implementation model* and the *application model*. The meta and reference model are based on the theoretical insights described in the previous section, whereas the implementation model corresponds to the *model of type* as described by RUPPRECHT. Together they describe the formal abstraction levels of iPeM. The application model represents no further formal abstraction, but implements the specification of an implementation model to monitor a executed process.[405] To fully exploit the potential of iPeM for situation specific process modelling, the concept of content related abstraction levels, according to the approach of RUPPRECHT, needs to be introduced.

As any content related level can be defined, it is necessary to review the scope of iPeM, i.e. main application cases in which it is used. These cases are of particular importance to define useful abstraction levels for the model based on its purpose:

- *Application in research* to support the investigation of product engineering processes for different domains or products i.e. as basis for scientific reasoning
- *Application in industry* for modelling and managing the processes in a special branch, company and special product developments.

The first level of the content related abstraction can be defined in a similar way for both application cases (Figure 7-3). On this *general* level, the iPeM meta model, as presented in section 3.2.3.2, is not further concretised in terms of content, but only formally abstracted. The results are patterns generally valid for any domain, such as an abstract formulation of an innovation process. This pattern can be customised for a specific project and monitored. This level is fairly abstract and only suitable for the investigation of abstract coherences between the model elements and relationships, since few operative processes can be generalised up to this level.

For an application in research, there are two further content related abstraction levels, seeming suitable for facilitating modelling effort and supporting situation (constraint) specific modelling. Referencing iPeM to a specific domain reaches up to the second abstraction level, the *domain specific* level. Contents of the meta model are tailored to include elements necessary to define models for a specific domain. These can be used to derive domain specific reference models, such as a specific engineering process.[406]

[405] see also Meboldt 2008, pp. 200
[406] cp. to Albers 2010, p. 10

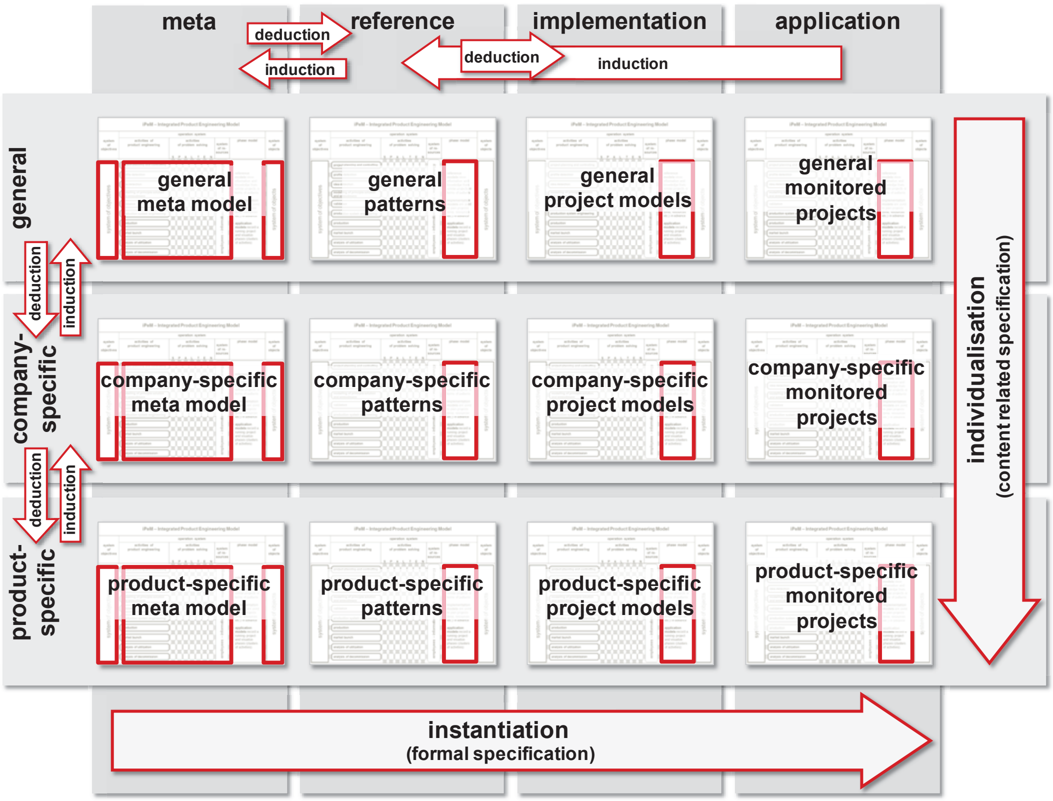

Figure 7-3: Different abstraction levels of iPeM (application in industry)

This meta model can be specified regarding its content to provide a toolkit of modelling elements and relationships to derive *product specific* models. These can be, for example, patterns occurring only in the engineering process of a car or a machine tool. A further formal concretisation allows a concrete specification of the identified pattern for specific constraints (implementation model).

For the second application case, a suitable content related individualisation of the general meta model would be a *company specific* level. Such an individualised toolkit constitutes the basis from which to describe anything that can be generalised to have company wide validity and is independent from specific product developments. This can be a company specific development process or quality management procedure (company specific pattern).[407] Such a pattern can be formally customised to specific project constraints. Finally, a *product specific* level, similar to the first application case, allows the formulation of product specific models which can be specified for operational implementation. The choice of a specific content related abstraction level, for building and specifying a model, highly depends on constraints of the actual application and generalisability of the model elements and relationships described.

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[407] See Chapter 8 for an example of a company-specific meta model (Figure 8-1), reference model (Figure 8-2, Figure 8-4), implementation (Figure 8-7) and application model (Figure 8-8). See also the example of the vehicle development process at Porsche AG (section 5.2, Figure 5-2).

Besides the ability of the modelling framework to tailor models to specific abstraction levels and make implicit model elements and relationships explicit, with means of a unified language provided by the meta model, the articulation of implicit model components and the adaptability of the model to changing constraints and insights, *during* and *between* applications in projects, needs to be ensured. This is done in iPeM using two procedures based on the principles *deduction* and *induction*. Deduction is understood as the "inference in which the conclusion about particulars follows necessarily from general or universal premises."[408] This is valid for the formal and content related specification of models. The derivation of a reference from a meta model has to be complete and consistent regarding the relationship of model elements and relationships provided in the meta model. This applies also to the individualisation of meta models on content related abstraction levels. The derivation of an implementation from reference models and the provision of a general model as framework to be individualised for a given context, needs to be useful to save effort in deriving models for specific constraints. Thus it does not need to be complete and consistent in terms of model elements and relationships. The application model matches the implementation model in the degree of formal abstraction. It is modified during process execution, in response to changed constraints, by adding, eliminating or modifying model elements and relationships. The application model can be used to articulate insights gained during the project and to convey the insights back to the reference model. This inductive procedure, understood as "inference of a generalised conclusion from particular instances,"[409] allows the evaluation of model elements and relationships, which specifically occurred in one or more concrete projects, to judge whether they can be generalised and incorporated in the reference model. If this holds true, integration into the meta model can be evaluated. Insights from lower content related levels need to be analysed, as to whether they are generalisable to a higher content related abstraction level, e.g. when a process proves to be execute in a similar way for all the different products within a company.

By using these procedures the modelling framework of iPeM, including the models derived on this basis, are adaptable to changes of constraints in and between projects, while being able to describe each situation specifically. This section showed that a modelling framework and its "building kit" for models, can never be complete. Suitability and usefulness depend on the sum of applications and experiences.

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[408] Merriam Webster Online 2010d, query „deduction“ (10/11/24)
[409] Merriam Webster Online 2010c, query „induction“ (10/11/24)

7.3 Extending the Systemic Thought in iPeM

The previous section laid the basis for the modelling approach by outlining the different abstraction levels of iPeM and procedures on how to derive models for those levels. This section extends the systemic approach grounded in iPeM to be able to describe systems of objectives and operation systems at all levels of abstraction. This extension shall also ensure adaptability by applying general insights from the prior section to these two systems as basis to describe the development of systems of objectives and the interface between the two systems in the next section.

Given the understanding of modelling as being a subjective, constructive activity, as outlined in section 7.1.1., the modelling framework of iPeM is based on several fundamental mental models. In providing those as components of the meta model and thus as means for the derivation of all subsequent models, the articulation, i.e. the mapping of an individual´s mental models to a formal representation shall be facilitated. The fundamental mental models relevant for this approach are systems thinking and macro and micro logic (representation of activities).[410]

7.3.1 System of Objectives

As Chapter 6 has shown, the development of systems of objectives is a mostly implicit, dynamic process depending on various influencing factors. In particular, the uncertainty of dynamically changing constraints impedes a systematic modelling of systems of objectives. Thus, this modelling approach aims to support this modelling procedure by the provision of a unified basic structure and language to articulate implicit system elements and map implicit relationships cast in the mental models of individuals to an aligned formal representation. This approach to model the system of objectives focuses on supporting modelling *during* process execution, providing the ability to extend and concretise the model in line with the system´s completion and concretisation. It strives to be able to integrate elements with varying formal, content related and temporal characteristics and to individualise models according to specific constraints. The approach builds on the framework of the iPeM (section 7.2), the general system postulations (section 3.2.1) and the findings from Chapter 6.

7.3.1.1 System Units of the Meta Model

The meta model provides system units and a methodology to assemble the units in a modelling framework to derive specific models. It provides a common language to articulate elements and relationships contained in the mental model of the modeller. This section outlines system units and rules of assembly for the system of objectives.

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[410] see also Meboldt 2008, pp. 200 and section 3.2.3.2

As known from existing systemic approaches (section 3.2.1.3), objectives can be described as *system elements,* since they are representable in hierarchical, structural and functional perspectives. Section 6.2.2 outlined that associated constraints are also part of the system of objectives and can be depicted with the same formal, content related and temporal characteristics. Thus, they are included in this approach as system elements to the system of objectives. The characteristics of objectives and constraints can be represented as the element´s attributes. This can be the different inherent properties of the information each objective or constraint carries, such as its measurability as formal attribute or its reliability as a content related attribute. Since the description of objectives and constraints as elements equals their articulation, no further differentiation between previously implicit and explicit elements is required.

Section 6.2.2 outlined that elements can be differentiated with regard to the content they address and that elements with similar content may be treated as clusters. If the content of each element is regarded as an attribute and attributes of different elements are connected by forming a cluster, then these elements must be part of a superior system (section 3.2.1.2). This supersystem is an abstraction of the content contained in each specific and potentially individual element. This system of content related affiliated elements is named a *section* (section 3.2.1.2) (Figure 7-4).

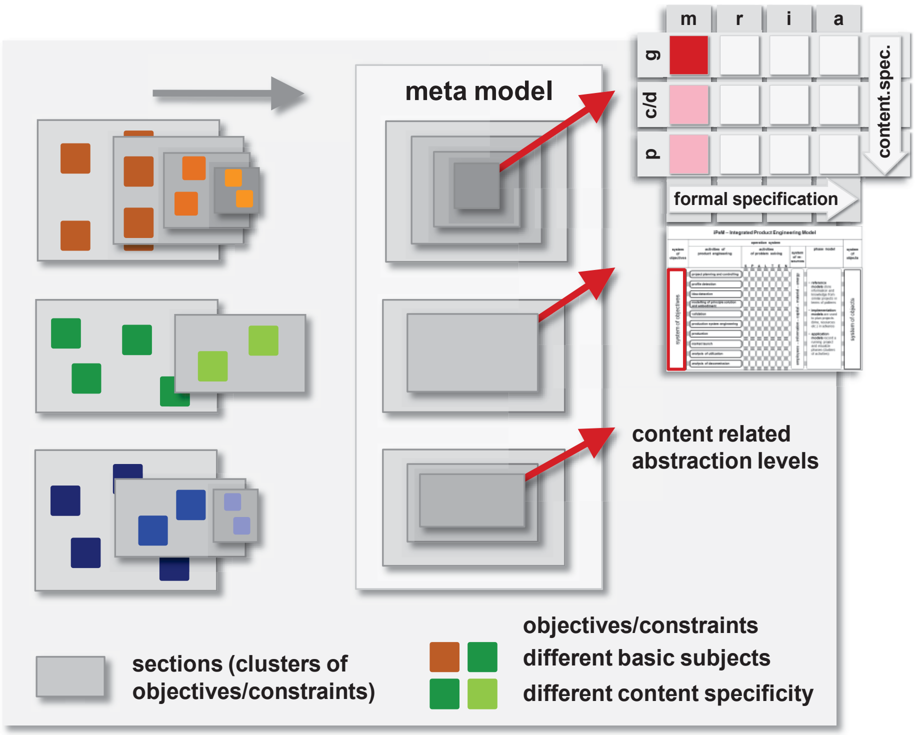

Figure 7-4: Hierarchical perspective, content related abstraction in system of objectives[411]

[411] The matrix on the right is subsequently used to give a reference on the respective abstraction level addressed in respect to the overall abstraction levels of iPeM (see Figure 7-3, names of model levels are abbreviated). The darker red highlights the explained, lighter red equivalent application.

Since elements in a system of objectives may contain similar content in different degrees of specificity, a hierarchy of different content related abstraction levels is required. Sections on different hierarchical levels are related to their superior level by an is-a, or is-part-of relationship. The hierarchy enables the allocation of an objective or constraint to the specific hierarchic level suited to the specificity of its content. Each level may contain different sections capturing elements with the same degree of specificity, but different addressed content. Sections on the highest abstraction level represent the most general differentiation between subjects addressed by the elements in a system of objectives, e.g. trends and technologic development. These basic sections differ in the abstraction levels of the content in the incorporated elements. Thus, the meta model needs to provide the building methodology for each hierarchy of the basic, generalisable content related sections in a system of objectives.[412] The meta model defines rules on how to describe a system element, but does not allocate elements to the basic hierarchies.

7.3.1.2 Formal Abstraction

As shown in Chapter 6, specific sections can be identified to reoccur as content related clusters of objectives and constraints in similar projects. Also some objectives or constraints are repeatedly matched to equal sections in different projects. Such a reoccurring structure is called pattern or reference model of a system of objectives. It can be modelled by using sections in basic hierarchies as defined in the meta model and modified to suit conditions for a specific type of project (Figure 7-5). This modification entails a formal specification of the sections. Dependent on the different subjects to be covered by the reference model, general sections from the meta model are duplicated (e.g. a first hierarchic level of the basic section *environmental constraints* could include sections for *legal* and *ecological constraints*). Objectives or constraints known to reoccur are allocated to respective sections suiting their content and specificity. In this case, a system element is defined according to the rules defined in the meta model and attributed to the given type of project (e.g. constraint *development of* CO_2 *emissions* is allocated to the section *ecological constraints*). Relationships between sections, objectives and constraints can be modelled taking a structural perspective on the system. Relationships can arrange sections and system elements dependent on their causal sequence or influence (e.g. *ecological* influence *legal constraints*, thus respective sections are related). Technological relationships can also be visualised (e.g. competing relationship between the objectives *weight* and *fuel consumption*). Relationships on lower abstraction levels need to be on higher levels to support the representation of a consistent system.

[412] cp. to Zangemeister 1973 (section 3.2.1.3)

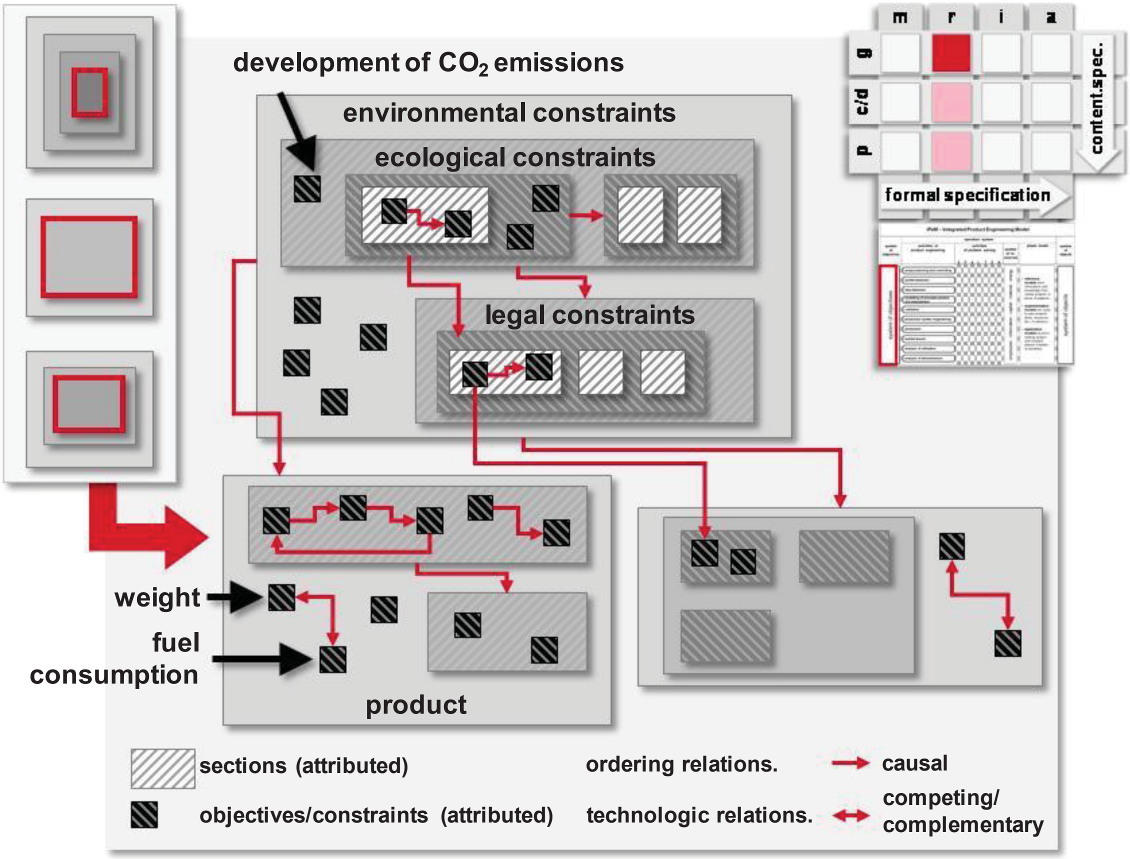

Figure 7-5: Structural perspective, formal specification of the meta model

A specific project model (implementation model) can be derived by further formal specification of specific sections, elements and relationships. This is done by concretising sections and elements with regard to specific project constraints (e.g. *development* of CO_2 emissions → *further rise/stagnation* of CO_2 emissions). This ensures that information required at the start of the project is integrated into the initial system of objectives.

7.3.1.3 Content Related Abstraction

IPeM provides the potential to tailor general models to more specific contexts, e.g. to derive models specifically suited to describe the development of a certain product. This enables the modelling of systems of objectives according to the individual conditions of a company or a certain product. For example, for a specific company, the sections of objectives and constraints on lower abstraction levels might be generalisable as basic modelling elements for that company (Figure 7-6). The validity of these sections (and of allocated elements in reference or implementation models), is limited to use in this context (company), e.g. a certain company might always collect information on *safety regulations* (subsection to *legal constraints*). Similar ideas apply for the individualisation of reference and implementation models, e.g. the pattern of sections and elements (Figure 7-5) can be complemented by company specific sections and elements on a company specific individualisation level.

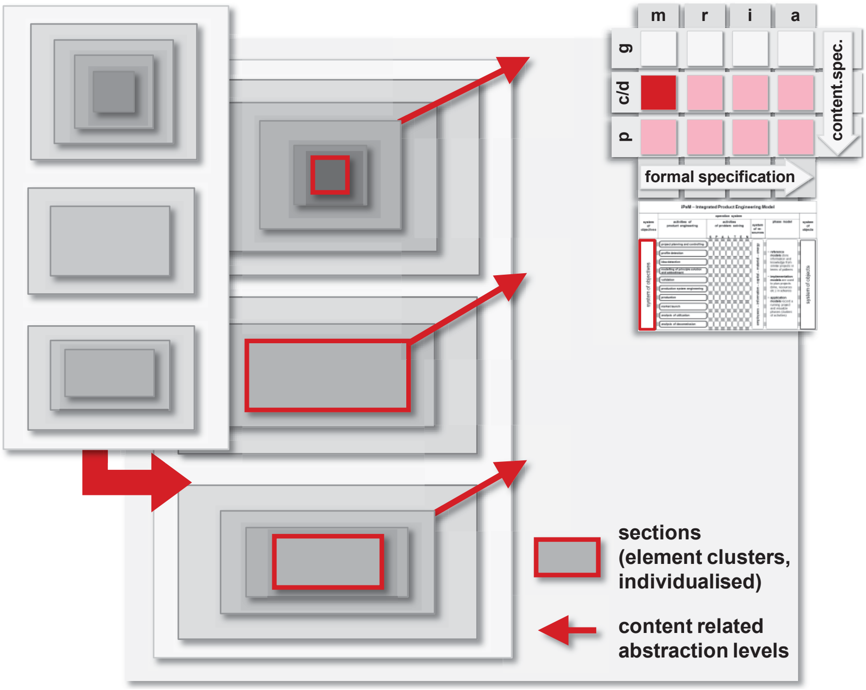

Figure 7-6: Content related specification of the meta model

7.3.1.4 Adaptability of the System of Objectives

Uncertainty, arising from changing constraints and other uncertainty inducing factors, was chosen to be accommodated by designing flexible systems (section 6.4.2.4). This flexibility needs to be reflected in the modelling approach for the system of objectives by providing the means to design models able to adapt to changing constraints. This means that systems (sections) and system elements, i.e. objectives and constraints need to be modifiable. Thus, their attributation (formal and content related characteristics) has to be adaptable to different concretisation levels (section 7.3.1.2 and 7.3.1.3). This ensures the robustness of the modelling approach during the completion and concretisation of the model between and throughout projects.

Secondly, the given structure needs to be extendable. This means that new sections, objectives or constraints as well as the relationships between them may be added. This is necessary if a reference model of the system of objectives is adapted to concrete project constraints in an implementation model. Thus, the model is built deductively. New or changed constraints may be needed to be integrated into the system as elements and may require a new content related cluster, or a new section. This model represents the initial system of objectives for a new project. The largest share of changes in system units and integration of new sections, constraints, objectives and relationships, happens in a project. This is modelled with the application model based within the same structure as described in the implementation model. The flexible definition of sections and elements, as provided by the meta model, enables situation specific adaptation of the application model using a common modelling language.

When finishing a project, the application model not only depicts the current state of the system of objectives, but also can be used for evaluating modified or added sections and elements on their generalisability. Certain sections, elements or relationships, only added or modified in the application model, might reoccur (or have reoccurred) in projects with differing constraints. This may permit the adaptation of the reference model by including these system units. It may even justify an adaptation of the meta model, e.g. if further hierarchical levels in the basic sections have turned out to be necessary in application (Figure 7-7). This direction of adaptation is inductive from project insights.

Adaptations on higher content related model levels can be passed down to lower levels. Equally, an integration of e.g. a new basic section and respective hierarchy in the meta model at a company specific level needs to be evaluated regarding its generalisation and inclusion within the general meta model. The set of sections and elements of a specific model is never complete, since it depends on the prevailing constraints considered. But since the model is adaptable to changing constraints, it supports the reduction of uncertainty by systematically allocating elements to appropriate content related sections. The concept fosters lean system development by avoiding the growth of the system's layout.

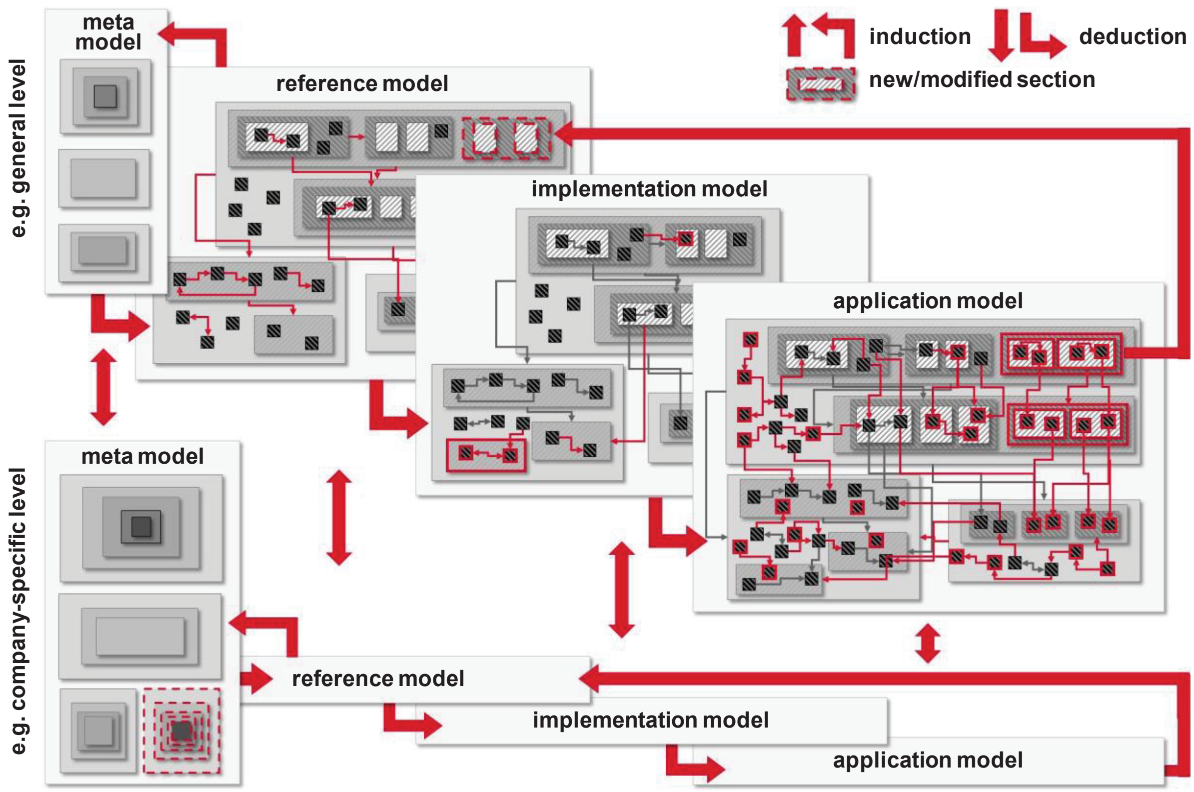

Figure 7-7: Adaptability of the system of objectives

7.3.2 Operation System

Previous sections in this thesis argued that the uniqueness of engineering processes, due in part to dynamic constraints, impedes the modelling and management of activities. In particular, activities concerned with the generation of objectives are often implicit and not actively planned and regulated. But, as shown in section 6.4, the active managment of activities has significant influence on the handling of uncertainty and the state of the system of objectives. To articulate activities and thus to make processes accessible to situation specific modelling and management, the current understanding of activities in iPeM is extended on a systemic basis. It shall provide means to build activity models on abstraction levels suitable to specific constraints and provide adaptability of the system. In contrast to the approach for the system of objectives, the focus for supporting the operation system lies in process *planning*. The following approach is based on mental models of micro and macro logic in iPeM and general system ideas. It focuses on modelling activities rather than on resources.

7.3.2.1 System Units of the Meta Model

The meta model needs to provide the means to describe all the activities of the engineering process. In iPeM, activities are modelled as part of the operation system in the activity matrix. To recap from section 3.2.3.2, the matrix is bounded by product engineering activities (macro activities), distinguishing main activities of the product engineering process, and the problem solving cycle (micro activities), performed to solve a specific problem. Following the systemic principle, an activity is a subelement to the operation system. Thus, an activity is part of the hierarchical structure of the operation system. Each activity transforms an input into an output, according to the functional concept of a system (section 3.2.1.2), whereas this output is itself input to another activity. Further, each activity has at least one predecessor and successor, relating activities and forming a structure (structural perspective). As an activity can be depicted with all different perspectives on a system, an activity of iPeM can be modelled as system or subsystem to the operation system. An activity can be modelled for different formal abstraction levels by specifying the attributes which it contains as system. Attributes to activities can be information, duration or responsible agents. The meta model contains only activities with unspecified attributes. Attributes are assigned when implemented in a specific model (next section).

According to HUBKA and EDER, an activity is decomposable into different content related abstraction levels, where the extent of the abstraction needs to be suitable to the key problem.[413]

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[413] cp. to Hubka & Eder 1996

Since the aim of iPeM is to provide the modeller with the means to model the engineering process situation specifically, activities need to be representable on different abstraction levels. Section 7.2 has outlined that the content of the meta model is concretised if the model is individualised to a specific level, e.g. product-specific. Since the meta model is built on systemic principles and thus its structure is built of related subsystems, a concretisation of the meta model can only take place if its subsystems, therefore also the activities, are concretised. Consequently, it has to be possible to derive activity models from the meta model with an abstraction level according to the relevant problem, i.e. a meta model has to provide the ”construction rules” for modelling different abstraction levels of activities.

Assuming that each macro and micro activity is a system, then each activity consists of subsystems, which exist of subsystems etc. If content related attributes of two sub-activities on a lower abstraction level are connected, a supersystem on a higher abstraction level emerges (section 3.2.1.2). According to systemic principles, such an arrangement represents a hierarchy (Figure 7-8). Subactivities of macro activities concretise the content related description of main product engineering activities (e.g. main activity: *profile detection*, potential subactivity: *trend analysis*, further subactivity: *global trend analysis*). Resulting hierarchic levels are defined by the different content related abstraction levels of the activities.

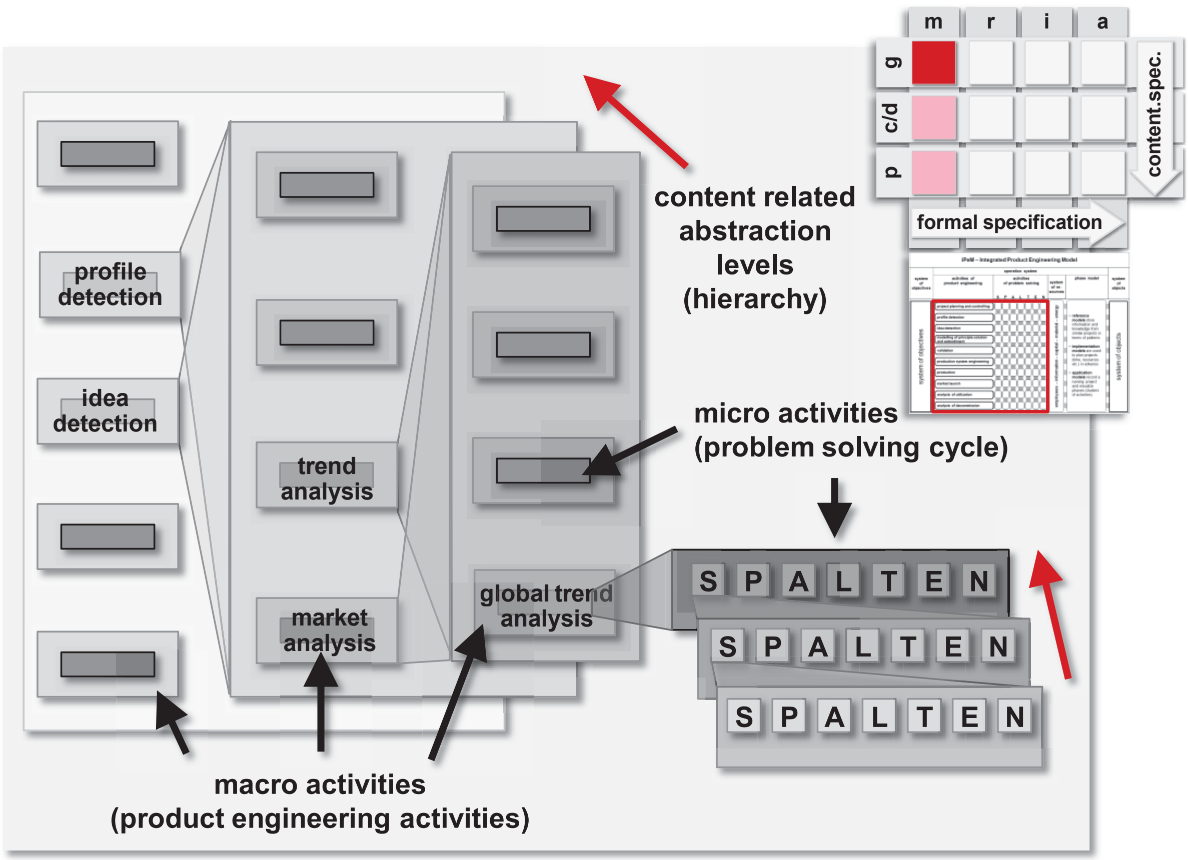

Figure 7-8: Hierarchical perspective, content related abstraction levels in iPeM

Each macro activity on a higher abstraction level contains *all* the subactivities on the lower levels and is itself part of all the activities on superior levels (e.g. the subactivity *trend analysis* is a subactivity to main activity *idea detection* as well as the superior activity to *global trend analysis*).

Each macro activity comprises *all* the micro activities of problem solving. Subactivities of micro activities concretise problem solving steps. *Each* micro activity implements another instance of the problem solving cycle (Figure 7-8). This is characteristic of activities in the operation system and is called *fractality*.

7.3.2.2 Formal Abstraction

A pattern of activities is a set of activities identified to reoccur in a certain arrangement with a specific attributation in different projects and process executions. They represent homogenous activity classes, also known as processes. Such a pattern can be derived using the elements and building methodology defined in the meta model (section 7.1.2, 7.2). Elements, containing the content necessary to depict the pattern, are selected from the corresponding hierarchic (content related abstraction) level (Figure 7-9). These elements, i.e. macro and micro activities, need to be formally specified. This means that they are attributed with regard to the constraints identified for their respective activity pattern and with regard to their sequence. Such an attributation can include the allocation of duration, but not a fixed start and end point in time (project independency) or the number of people scheduled to run this activity, but not specific individuals. Treating activities as systems, this procedure can be modelled from using a structural perspective. Activities are arranged by defining relationships between them, and may be structured with regard to their timely and causal sequence.

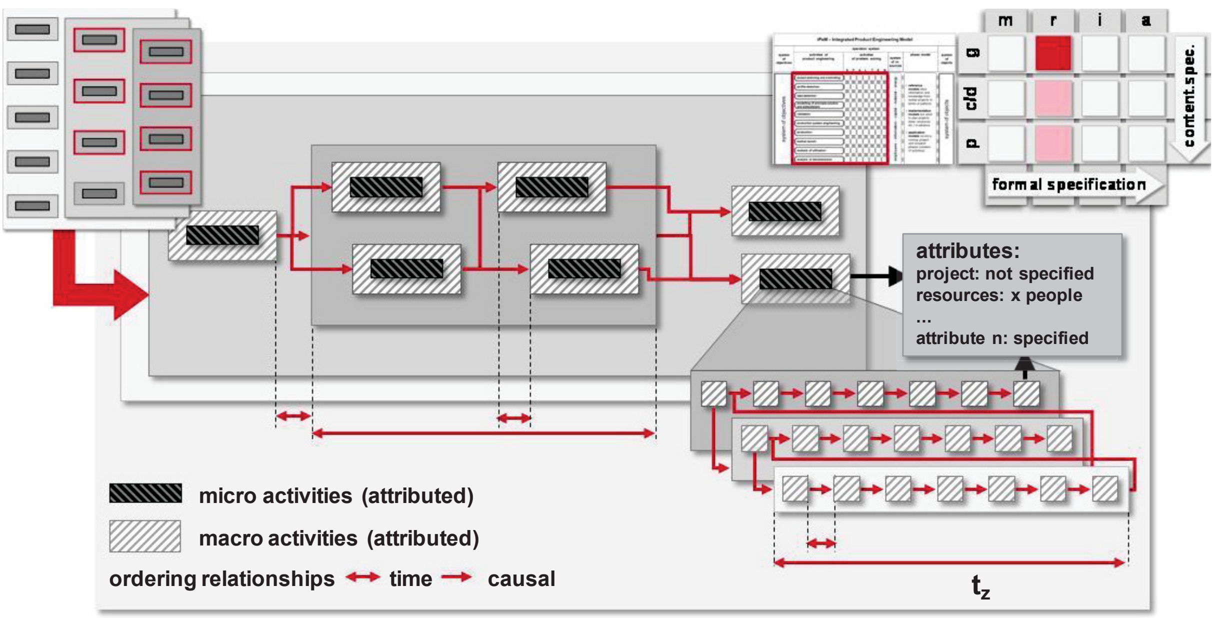

Figure 7-9: Structural perspective, formal specification of the meta model

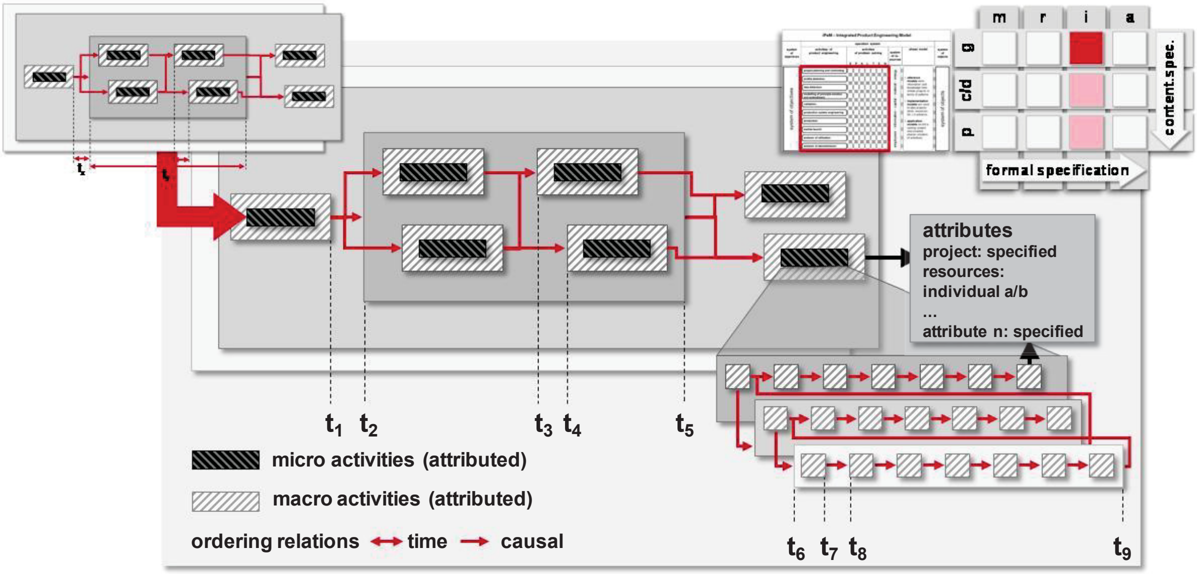

Figure 7-10: Structural perspective, formal specification of the reference model

Relationships on lower hierarchy levels need to be indicated on higher levels to ensure consistency. Micro activities can be modelled equally. Each macro activity always implements a full conduction of problem solving activities on all abstraction levels.

A model for a specific project, an implementation model, can be derived from a formal specification of the systems and their relationships (Figure 7-10). This is done by concretising activities with regard to specific project constraints. Thus, e.g. specific start and end points of activities can be assigned or specific resources be allocated.

7.3.2.3 Content Related Abstraction

According to section 7.2, iPeM can be tailored to reflect specific content related scope, e.g. as a company specific meta model. This enables an extension of the meta model to include activities generalisable for a specific company, but not to a general company independent level. Consequently, these activities are assigned to a more specific content related abstraction level in the meta model (Figure 7-11, next page). The validity of the activities as meta model elements is limited to their use for that specific scope, e.g. a certain company. An individualised model of reference or implementation models can be derived in a similar way. Sequences, as in Figure 7-9 or Figure 7-10, can then be complemented with company specific activities from the meta model.

7.3.2.4 Adaptability of the Operation System

CHALUPNIK found that protecting a system by increasing its flexibility is the most effective strategy to deal with uncertainty in engineering processes with dynamic constraints (section 3.1.4.3). Section 6.4 stated that such flexibility is essential to support the handling of uncertainty during the generation of objectives.

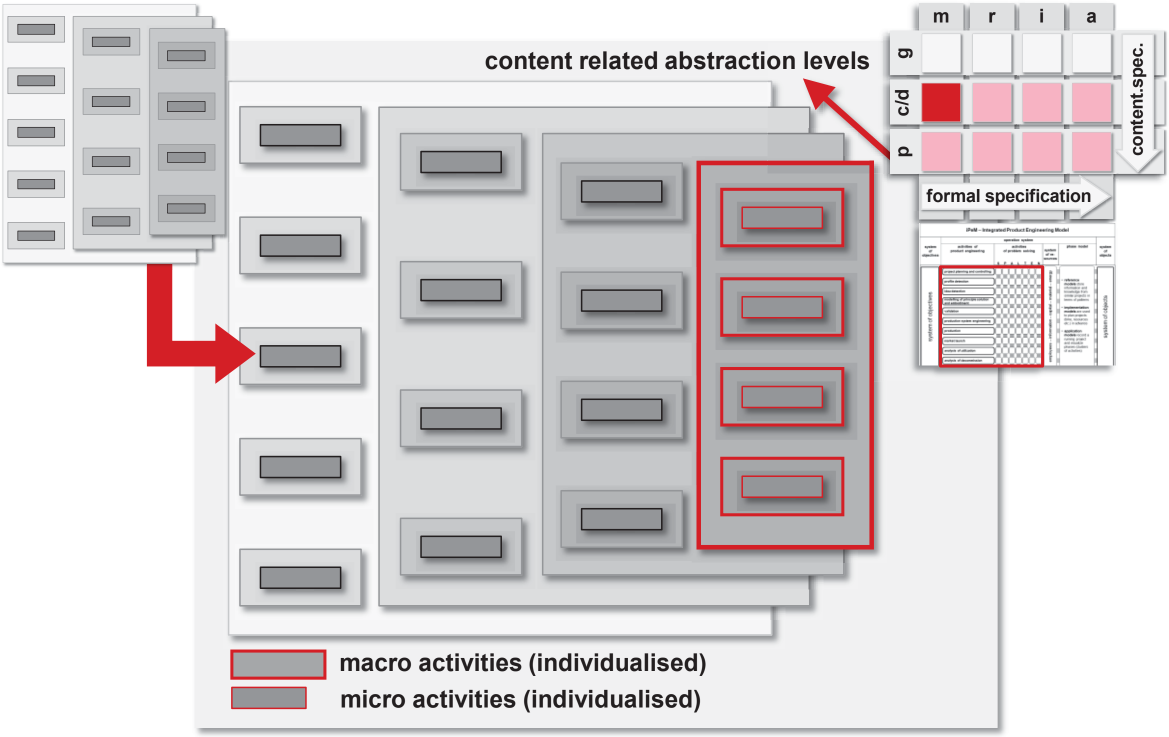

Figure 7-11: Content related specification of the meta model

Thus, an approach to support the modelling of activities concerned with generating objectives needs to be adaptable to changing constraints between and during projects. The ability of an activitiy as a system to react to changing constraints in formally concretising its attributes is one form of adaptation (Figure 7-10).

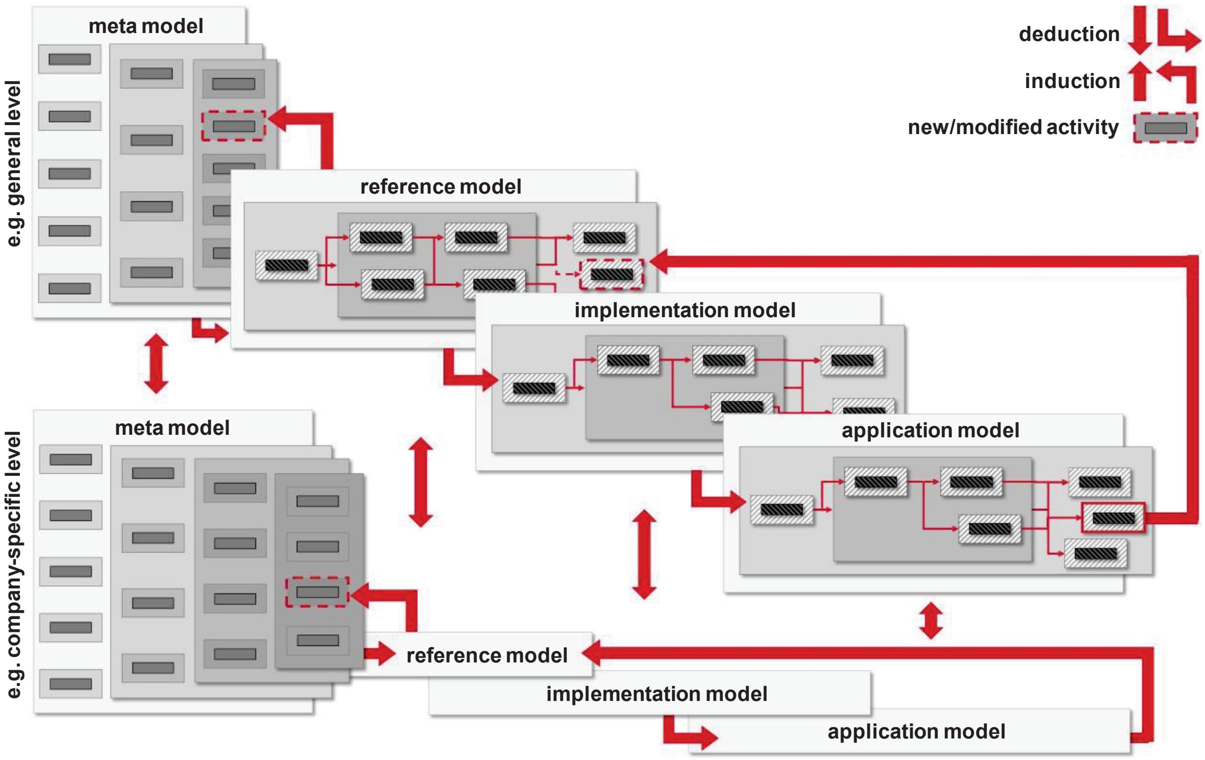

Figure 7-12: Adaptability of the operation system

Further forms are *adding*, *deleting* or modifying (adapting attributes) an activity or relationship. Such adaptations of the operation system are made deductively by deriving a model from a higher abstraction level or inductively from project insights (Figure 7-12). This is monitored in the application model, based on the implementation model´s layout. The model can adapt to changes during the conduction of the process by integrating new or modified activities. After finalising a process, it is to be questioned whether activities in the application model, deviating to the depiction in the reference model, became necessary due to specific project constraints. If not they may be evaluated regarding generalisability and potential integration in and adaptation of the reference model, and if applicable even an adaptation of activities in the meta model. Changes in the meta model on a higher content related abstraction level might cause an adaptation of meta models on lower levels (deduction). A modification in a meta model on a more specified individualisation level needs to be questioned whether this change is generalisable to the meta model on higher abstraction level. The set of activities in the meta model is dynamic, developing in line with the knowledge associated with the product engineering processes. Thus, it is never completed and information transfer about occurring activities, attributes and relationships can be ensured to keep the model complying with constraints in constantly changing product engineering processes.

7.4 Modelling the Development of Systems of Objectives

The previous section has served to introduce modelling tools and procedures which describe both a system of objectives and an operation system. Before these insights can be merged to derive a meta model as basis for describing the development of the system of objectives, the interface of the two systems needs to be looked at to be able to visualise the actual process of developing objectives. Sticking to systemic premises, this requires taking a functional perspective on both systems to analyse relationships between system of objectives and operation system.

7.4.1 Interface between System of Objectives and Operation System

7.4.1.1 Outer Structure

Section 3.2.1.3 has introduced the system of product engineering as system triple in which a system of objects is developed by an operation system according to the premises of a system of objectives. The operation system is linked to the system of objectives. In parallel, the system of objectives provides input to the operation system. The environment is illustrated with an influence on the entire system triple.[414]

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[414] cp. to Ropohl 1975, see also Figure 3-9

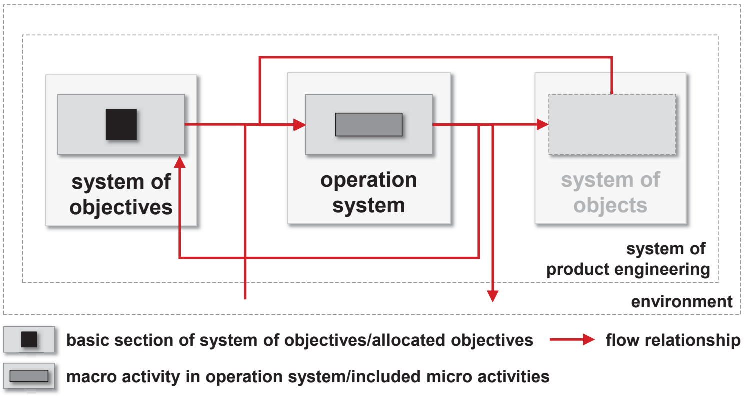

Figure 7-13: Interactions in the system of product engineering

Figure 7-13 uses this concept as basis to model the interface between the systems of product engineering. Seen from a functional perspective, the systems are defined by their input, output and respective states. The output of one system is input to another, thus the relationship can be seen as flow relationship between the systems.

Since the system of objectives is abstract, it can only absorb, process and emit information.[415] Thus, all flow relationships subsequently looked at are of the type *information*. The system of product engineering is not regarded as being closed loop in this approach. Since the system of objectives is abstract and the system of objects is passive, i.e. not acting, an active integration of information from the environment and release into the environment must be triggered by the operation system. As previously stated, relationships between systems on the lower levels need to be visualised on higher hierarchical levels to ensure consistency. Consequently, relationships on the highest hierarchical level must indicate relationships between subsystems on lower hierarchical levels. Thus, the input of the system of objectives from the operation system originates from a macro activity, directly linked to a subsystem within the system of objectives. The input from the operation system changes the state of the system of objectives by integrating new objectives, constraints or relationships between them and by concretising it by modifying existing system units.

The entity of all system elements and relationships represents the current state of the system of objectives. Information included in this state, about the state of the system of objects and the environment, serves as an input to the operation system, i.e. a specific macro activitiy. The main function of the macro activity is to transform provided information into objects. As well as new or modified objects, the activity generates new or modified constraints or objectives to be integrated in the system of objectives.

[415] flow relations between operation system and system of objects can also be, for example, material

The results developed by activities can themselves only be provided for the environment by another activity of the operation system.

Subsystems of the system of objectives and operation system can be concretised for further content related abstraction levels. Since they remain subsystems to the basic system, a description of the interface, as just outlined for the basic abstraction level, can be transferred to each further abstraction level. The following definition applies:

> **Definition 7-1: Interface System of Objectives and Operation System**
> The interface between the system of objectives and the operation system can be depicted as (bidirectional) information based relationship between a specific section of the system of objectives and a specific macro activitiy of the operation system on any content related abstraction level of the subsystems.

This definition supports findings from section 0 that the development of the system of objectives is triggered by activities from the operation system. Chapter 3 and 5 revealed that the development of systems of objectives is a unique process to which differing activities on different levels of abstraction contribute. But since the interface as defined can be transferred to any content related concretised subactivity, a specific activity, contributing to the development of the system of objectives and its link to an addressed section in the system of objectives, can be explicitly modelled.[416]

7.4.1.2 Inner Structure

The prior section has shown that an interface between an activity of the operation system and a section of a system of objectives system can be modelled by taking a functional perspective on the systems. The following paragraphs outline how the link between a specific activitiy and a specific section, and the respective elements of the system of objectives, can be defined. This is done in taking a further look at the inner structure of the two systems (hierarchical and structural perspective). The system of objectives is illustrated with examples of objective sections, elements and relationships (Figure 7-14). The analysis of systems of objectives (Chapter 6) revealed generalised steps in their development that resembled activities within a problem solving process. Thus, these can be depicted with the micro activities of the SPALTEN methodology in iPeM.[417]

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[416] see also Albers et al. 2010f

[417] for a description of the SPALTEN methodology, see section 3.1.5

If a macro activity as (a subsystem of) a product engineering activity of iPeM includes micro activities as subsystems, the development of systems of objectives can be modelled with micro activities and an interface of a macro activitiy and a system of objectives can be depicted as information based relationship, then the following definition applies:

Definition 7-2: Development of System of Objectives in iPeM

Since each activity in the development of a system of objectives can be described as a subactivity in the activity matrix of iPeM comprising all micro activities of the problem solving process, the development of a system of objectives can be modelled using the framework provided by iPeM.

Each macro activity comprises a problem solving cycle. The first step in a SPALTEN problem solving cycle starts with *situation analysis* (S, Figure 7-14, (1)).[418] Due to the previously mentioned fractality of the micro activities, the execution of the situation analysis can be understood as a subordinate problem solving process on the second content related abstraction level ((2) onwards) which is assigned to the superordinate activity (e.g. situation analysis (1)) with a hierarchical ordering relationship.

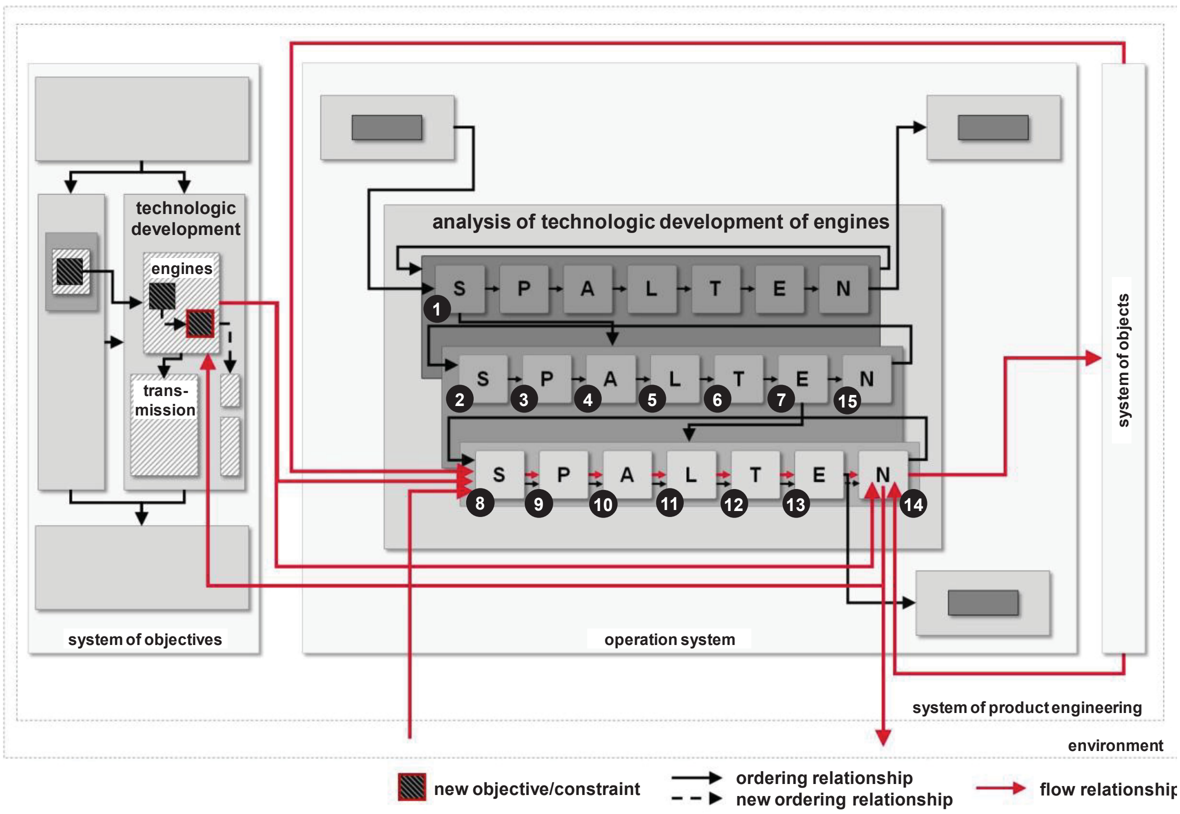

Figure 7-14: Inner structure interface between system of objectives and operation system

[418] see also Albers et al. 2005a, Saak 2006

According to section 6.3.1.1, a situation analysis in the development of objectives serves to define the scope of the problem, i.e. the maximum reducible epistemic uncertainty and to collect information from the environment necessary to build the system. This process is depicted on the second hierarchical level (2 onwards). The actual processing of the content of the information exchanged between the systems is done by the individual, as problem solving, as predominantly implicit, mental activities. These activities represent the actual capturing and interpretation of reality in mental models as well as making of decisions, as described in section 7.1.1. The articulation of such activities can be attained by using a third content related abstraction level of the problem solving process ((8) onwards). Since these activities are predominantly mentally (implicit) and are thus inevitably interlinked, the information flow is depicted as a flow relationship between the activities on the third hierarchical level.

At first the scope of the problem is identified; this defines what is to be solved during the situation analysis (2). In the example in Figure 7-14, the scope would be an analysis of the future technical development in the field of engines. Next, the initial state of the system of objectives and the system of objects is identified by collecting currently available information from both the systems. In the example, there is one information element regarding the technologic development of engines currently available in the system of objectives. The corresponding section is related to sections already included in the system, partly carrying further information.

This information is evaluated against the scope of the task (P, (3)), which in this case shows the necessity to collect further information from the environment on the future development of engines. The search for alternatives (A, (4)), their selection (L, (5)) and evaluation (T, (6)) describes the definition of the procedure, including the application of suitable methods and tools, which were found to be necessary by the problem solving team or individual. In this case, a suitable procedure for gathering information as well as potential sources or databases is defined. As found in section 6.3.3, the micro activity *decision and implementation* (E, (5)) actually performs the modification of the state of the system of objectives. Thus, this activitiy is taken as an example to outline the respective problem solving steps on the third content related abstraction level.

The situation analysis on the third level starts by adopting the premises as defined in the previous steps on the second level (S, (8)). According to these premises, information from the relevant section of the system of objectives, system of objects and the environment is collected. As visualised in Figure 7-14, the actual information flow between the system of objectives and the operation system always happens on the third content related abstraction level (indicated by red arrows, (8)).

The corresponding section in the system of objectives relevant for information provision and deposition for this specific macro activitiy is identified, when the scope of the macro activity on the basis of its content is defined. For example, in this case the relevant section for the activity *analysis of technologic development of engines* is in the subsection *engines* in the supersection *technologic development.*

So whenever information from the system of objectives is required in the situation analysis on the third hierarchical level, the activity draws information from this section in the system of objectives. Elements contained in this section and elements from related sections are available as input information for the micro activity.

Integrated information elements are compared to the scope demanded by the activity e.g. collect entire available information on the technical development of engines (P, (9)). The succeeding activities (A (10), L (11), T (12)) search and evaluate solutions on how to implement the information in the system of objectives (system of objects).

The actual decision (E, (13)) finally determines which of the collected information elements is transferred into the system of objectives (and system of objects) or whether further information needs to be collected in another, different macro activitiy. In this case, the primary problem solving cycle would be continued as soon as the other macro activity was finalised and the information transferred into the system of objectives (system of objects).

Finally, it is detected whether there is a deviation between the demanded scope and achieved results. This is done by importing the current state of the corresponding section of the system of objectives and of the system of objects to account for potential changes in the systems. If the deviation is acceptably minimised, the information can be transferred to corresponding sections (red arrows, N, (14)). If not, the problem solving cycle needs to be iteratively repeated (black arrow, (14)).

Based on these insights, the following definition for the information related interface between the system of objectives and operation system can be defined:

Definition 7-3: Information Exchange

The actual exchange of information between the system of objectives and operation system happens on the third content related abstraction level of the SPALTEN problem solving cycle. Reference to the section addressed in the system of objectives is defined by the scope of the macro activity.

If the problem solving cycle on the third hierarchical level has been completed, the next micro activity on the next superior level follows (in this case N (15)). This activity ensures the articulation and transformation of insights not yet integrated into the system of objectives (system of objects).

It is further decided, whether enough information has been collected as basis for the further development of the system of objectives.

Based on these insights the definition of a macro activity is extended (Definition 7-4).

> **Definition 7-4: Macro Activity**
> A macro activity of the operation system of iPeM integrates input information from the system of objectives, the system of operation and from the environment. The transformation of objectives into objects as well as the completion and concretisation of the system of objectives happens by undertaking three content related abstraction levels of problem solving.
>
> Explicit activities are not interlinked by information related flow relationships, but by causal ordering relationships. They integrate information directly from the system of objectives, system of objects and environment. Implicit (mental) activities are related by a mental information flow and causal relationships.

The preceding description has outlined the content of each problem solving step with respect to the development of objectives. In reality, these steps are carried out more or less consciously and also activities on upper levels might be conducted implicitly. The classification presented serves as modelling support for describing the activities performed to develop objectives and for eliciting implicit activities. Past explanations have shown that the interface between system of objectives and operation system can be modelled by referencing the specific section in the system of objectives with the respective macro activitiy. Such a reference is a content related relationship and is time independent. Thus, information can be systematically integrated into the system of objectives and retrieved i.e. complemented by new information from the operation system throughout the entire process (ensures completeness). Since the modelling of all micro activities of a macro activity down to the third hierarchical level is not always helpful, due to the effort required, the information flow to and from the system of objectives may also be visualised on the upper hierarchical level. On this level, the methods and tools used for a specific activity can be assigned.[419]

7.4.2 Meta Model for the Development of Systems of Objectives

This section merges the insights from the previous sections to propose an extended meta model of iPeM, focused on providing the means to model the development of systems of objectives in the early engineering stages.

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[419] The assignment of methods and tools to activities is not further depicted in this thesis, but is subject to previous (e.g. Saak 2006) and further research.

Figure 7-15 shows an overview of the system of objectives and operation system in this model. The aim in the development of this model was to reduce redundancies in the basic structure of objective sections and activities. The division of sections in the system of objectives was made according to the proposed classifications of exogenous and endogenous constraints as discussed in section 3.1.3.

Thus, there are two basic sections to cluster exogenous constraints, *environment* and *market*. On a further content related specification level, environmental constraints are clustered into sections, such as *economic* or *socio-cultural* constraints. These comprise also the constraints regarding trends which had been distinctly described in the project example used in Chapter 6. Market constraints can be further divided into constraints resulting from the *technological development*, from the *customer* and from *competition*. Endogenous constraints and objectives are represented by the section *company*. Here, the meta model suggests the clustering of constraints on a further content related specification level into *strategical* and *technological* constraints.

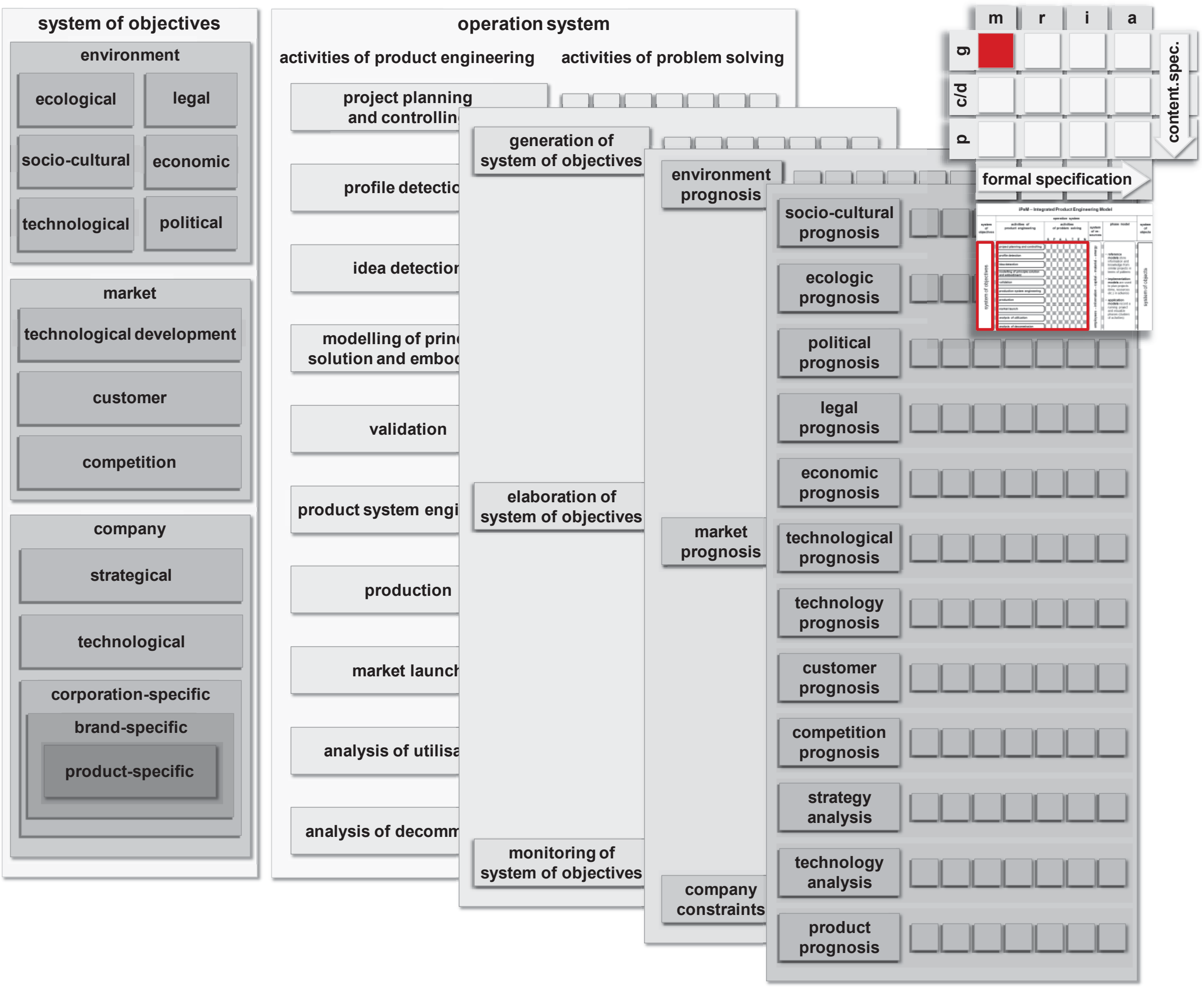

Figure 7-15: Meta model of the development of systems of objectives

Also clusters are proposed which depict the embedding of the product in the organisational structure to be able to allocate constraints and objectives according to their content related validity (e.g. objectives of *cooperation* vs. specific *product* objectives). It was decided to structure sections from the top down, according to the validity of specific sections. Thus, generally valid sections (e.g. environment), which influence most other constraints, are located at the top, whereas specific sections (e.g. product) are visualised at the bottom of the figure (Figure 7-15, cp. to section 6.3.3). This was done to facilitate the derivation of influences between the sections and elements in the system of objectives as a potential reference model. It could also ease the timely arrangement of activities in a reference model. This was done to ensure that generally valid contents of the system of objectives are elaborated and thus are disposable as early as possible in the process to be considered, in sections which are influenced by these contents (e.g. general technologic development as an influence to a competitor's development strategy).

In the operation system, iPeM is extended to a further abstraction level of macro activities. It was decided not to define a new macro activity *development of system of objectives* on top of existing macro activities due to the findings in section 6.3.2. They revealed that there are in fact characteristic stages in the development of systems of objectives, but that they are not assignable directly to product engineering activities. Thus, the generation of objectives might be mainly performed during profile detection, but may also take place e.g. during idea detection and even to some extent during the modelling of the principle solution and embodiment. The definition of the three main subactivities *generation*, *elaboration* and *monitoring of system of objectives* allows for a situation-specific derivation of reference models, since each of these activities might be allocated to any superior macro activity. A further content related specification leads to three subactivities which can be directly referenced to the respective sections in the system of objectives (e.g. environmental prognosis → section *environment*). The last specification orients itself towards further sections in the system of objectives (e.g. ecologic prognosis → section *ecological* (constraints)).

The two previous hierarchical levels serve mainly to be able to classify the activities on the most specific level as contributing to the development, e.g. generation of objectives, since they could also contribute to the other main macro activities (e.g. legal prognosis for homologation purposes). Procedures to validate the system of objectives are seen to be implicitly included in the problem solving procedures of described subactivities (cp. to previous section). The meta model does not explicitly describe the second and third specification level of the problem solving cycle, for reasons of clarity. However, they are implicitly included in each activitiy.

7.5 Insights

This chapter has proposed an extension of the modelling framework iPeM on a systemic basis to address the fourth research question and to be able to make objectives, constraints and their interface to corresponding activities explicit and thus to make the generation of objectives accessible to operative modelling, management and improvement.

It was argued that different formal and content related abstraction levels in a modelling framework and procedures to derive and adapt a model, both deductively and inductively from project insights, are necessary to be able to depict the process and its elements situation specifically and adapt it to changing constraints. Consequently, the proposed approach built on these requirements and developed a systemic framework to model a system of objectives and its interface to the operation system embedded in iPeM. The meta model presented represents a sound basis to improve the generation of objectives by supporting the completion and concretisation of the system of objectives. This is achieved by providing structured sections for allocating constraints, objectives and their relationships and by being able to retrieve them by reference to their corresponding activities in the operation system. It further fosters the validity, consistency and comparability of the system of objectives by providing the means to transparently describe the development of objectives in a uniform language.

8 Application to the Empirical Case

The approach of this thesis, as developed in Chapter 5, 6 and 7, was implemented within a practical case study to evaluate its applicability and verify its suitability to fulfil the research objectives (Chapter 4). The example used was the industrial environment of the car manufacturer Porsche AG (Chapter 5). This section outlines the application of the approach with the specific aim to improve the consideration of constraints identified in the environment analysis and prognosis in the generation of objectives at the company. Thus, it outlines how the potential to reduce uncertainty, based on identified deficiencies in the given process, were detected and how these had been exploited in adapting the developed approach to company specific constraints. This section concludes that the developed approach fulfils the defined research objectives since it supports the generation of valid systems of objectives aligned to relevant constraints for designated decision situations, while enabling an efficient and flexible handling of this process.

The implementation of the approach was carried out in the department responsible for the environment analysis and prognosis. It was synchronised with internal reorganisation measures initiated by senior management during the course of the research collaboration, based in part on the findings of the author (Chapter 5). Thus, a superior objective for improvement measures was set to guide the reorganisation process. It was based on the initial aim of the collaboration to improve quality of the system of objectives and to support its efficient, flexible development (section 5.1.2).

> **Definition 8-1: Objective of Improvement Measures**
>
> The consideration of results from the environment analysis and prognosis of objectives shall be improved by enhancing their quality and supporting their appropriate integration within the overall process of generating objectives.

Based on the insights from Chapter 5, an implementation of the approach developed in this thesis needs to consider the following requirements:

- *create awareness* of elements contributing to the objective generation process
- *increase knowledge* on how to handle and manage these elements
- *provide support* in handling the process

These objectives were realised by building on existing methods and tools, complemented by a pragmatic implementation of insights from the approach and by linking decentralised activities, methods and tools by using this systemic approach.

8.1 Accessing and Improving Process Contents

As a first step towards improving the given process environment, results from the empirical study from Chapter 5 were evaluated. A strategy was formulated, describing how the objective for improvement measures could be achieved by reducing given deficiencies. One main point of criticism had been that the results from the environment analysis and prognosis were not provided in a form suitable to be integrated in the generation of objectives. Therefore, it was determined that activities of the process formerly executed separately from each other were to be targeted towards the achievement of an overall result. Thus, all intermediate results were to be linked to finally create a so called *objective frame*. This frame was defined to provide a sufficiently complete, specified and valid description of the future product environment. This description would enable responsible individuals to use the frame as a recommendation for action regarding the derivation of their own objectives or other product relevant decisions.

To implement this approach by improving the given process environment, strategies to access and improve the generation of objectives, as proposed in section 6.4.2, were applied. This section discusses the exploitation of this potential to reduce uncertainty in the restructured process, while the next section will outline how the restructured process was standardised for operative modelling and management.

8.1.1 Articulation and Identification of Success Factors

According to the procedures proposed in section 6.4.2, it is first necessary to become aware of elements contributing to a process before it is possible to improve it. This requires the articulation of constraints handled and objectives, as well as respective activities, methods and tools. In this case, this had already been done as part of the empirical study (Chapter 5) of the process, as it was conducted so far. These results could be used directly (e.g. depicted system of objectives (Figure 2-2), processes (Figure 5-5)) to define a near complete picture against which relevant constraints may be considered, both now and also in the future, in the derivation of an objective frame and which appropriate activities, methods and tools were used to derive them.

To complement this picture and find out which constraints in fact had an influence on market success of a product and which of these factors had been neglected in the environmental analysis and prognosis, projects in which the developed vehicle for which the system of objectives was derived was already on the market were studied. The constraints initially assumed to be relevant for the future product were compared to the current market position to identify success factors. The results on the one hand gave information about the scope which needed to be taken into account for the derivation of an objective frame and on the other about constraints and objectives which needed to be considered independently of the project (e.g. global trends).

8.1.2 Identification of Uncertainty

The sources potentially leading to uncertainty during the environment analysis and prognosis had been identified in the empirical studies (Chapter 5). Effects they could have had in a generation of an objective frame, if they were not respectively treated, are briefly summarised. Since activities had predominantly been conducted implicitly and the generation of specific intermediate results could not be controlled until now, a target oriented derivation of overall results, as demanded for the frame would be difficult. This was further complicated by the lack of perception of the system of objectives as entire, coherent system. Predictions had been usually made at single points, which reduced the validity of the results. A lack of systematic methods to identify dependencies between constraints interfered with the aim for consistent results. Differing procedures, as observed among contributing individuals, would limit the results´ comparability. A potentially possible degree of completion and concretisation of the system of objectives in the process would be further limited, since existing tools were not able to handle the high level and differing types of information and knowledge, and to make them accessible to individuals. In particular, the lack of support to identify dependencies between constraints reduced the possibility to create a consistent objective frame. Limited exchange between responsible individuals and lack of knowledge with regard to transparently evaluating and handling uncertainty in information further represented a source of uncertainty.

8.1.3 Reduce Uncertainty

Before a reference process for the generation of an objective frame could be defined and appropriate activities, methods and tools standardised, identified sources of uncertainty had to be assessed to increase chances of mitigating potential negative effects. Since that assessment was to be made as part of restructuring the entire process, this opened up the possibility to exploit a maximum potential of uncertainty reduction, which might have not been possible using fixed process structures.

The first step involved the identification of those activities essential to the derivation of an objective frame. It was found that all activities shown in Figure 5-5 are required, but due to the lack of opportunity to actively control activities, they had not been executed optimally to provide results aligned to succeeding activities (e.g. results from monitoring trends are helpful in deriving the potential future development of technologies). Thus, a suitable timely arrangement of activities, in line with the range of validity of their results, was concluded to be necessary. In addition, a consistent development of an objective framework throughout the process was found only to be achievable if explicit activities are defined to control the execution of the process, and to combine the distinct intermediate results of the various contributing individuals to ensure consistency, coherence and a target oriented development of results.

Consequently, responsibilities for single activities were defined as well as points of reconciliation, respective intermediate results, information (repeatedly found to be necessary for specific activities) and needed methods and tools.

Identified uncertainty factors had revealed that given methods were not optimally aligned and suited to support a consistent completion and concretisation of the system of objectives, while ensuring a unified quality standard. To support a coherent elaboration of results, it was found to be necessary to develop methods to facilitate the identification of the coherence between constraints and to derive consistent and measurable results transparently. One relief to these shortcomings was found to be the introduction of a systematic definition and use of development scenarios. It was identified that pointing out *several* potential development scenarios, in particular for the relevant competition, and a transparent description of the uncertainty relating to the scenarios likelihood of occurance would represent significant additional value for evaluating alternative development scenarios for a product.

To be able to efficiently execute defined activities and methods, the requirement emerged for adequate information and knowledge management support. Such support was required to be able to describe the high level of information handled with varying properties. It should further support the indication of influences between information elements, according to their influences in the system of objectives. Such an information system was required to provide suitable and flexible data structures to describe dynamic elements and relationships. Finally, the efficient handling of explicit constraints, objectives as well as planning and management of respective activities could only be possible with suitable tool support.

Regarding handled information itself, a reduction in uncertainty was to be achieved by supporting the articulation and transparency of information, especially in decision situations. The realisation of this aim was found to be critically dependent on the provision of suitable tools and methods. Reliability of information was to be improved by supporting the selection and evaluation of sources with respective to methods and tools and an increased availability of information. A special focus was placed on supporting the systematic quantification of information during the process in order to reduce fuzziness and ambiguity and to improve the measurability of information.

Uncertainty introduced by the individual in the process was found to be reducible by supporting reconciliation across teams at defined points in time and by supporting decision situations with a transparent description of remaining uncertainty. The provision of a suitable framework of activities, methods and tools on the basis of unified expressions, was found to be a necessary condition to support systematic procedures. An essential factor in reducing uncertainty was to ensure the exchange and increase of prior knowledge by supporting the reconciliation of knowledge across team members and the inclusion of knowledge from prior projects.

The identification of the potential for reducing uncertainty served as a basis for adapting the iPeM modelling framework, as presented in the previous chapter, to the actual conditions within the company for describing the process of generating an objective framework. Identified constraints, objectives as well as activities could now be structured using the systemic methodology of the framework.

8.2 Developing Process Support

8.2.1 Individualisation of the Meta Model to the Application Case

The basis for the development of a modelling approach to support the objective frame generation process, were the insights gained as previously described, particularly from case studies at Porsche AG (Chapter 5) and from the extension of the iPeM modelling framework (Chapter 7). The aim was to describe the objective frame generation process as reference model within the iPeM modelling framework to enable management and improvement of the process. This process is a company specific process, since its setup and scope is specifically oriented at the conditions at Porsche AG and cannot be depicted on a general model level. Since this process was to be conducted for all products developed within the company, the model was defined on a company specific content related specification level. Thus, the meta model (Figure 7-15, section 7.4.2) was to be individualised to company specific constraints.

To identify modifications required for the initial meta model, constraints, objectives, activities and their relationships, elements identified in the previous section as being content related and relevant for the objective frame generation had to be reconciliated with the set of sections and activities predefined in the meta model. An extension of the meta model was required to concretise the new set of elements to a state, in which the individualised meta model is able to derive reference models for any company specific process pattern that is known to be executed during the generation of objectives at Porsche AG.

Previously identified project independent constraints and objectives were assigned as elements to predefined sections in the meta model which align with their content, e.g. the constraint *comfort demands of customers* was assigned to the section *customer*. This procedure had two effects. At first, the content related scope was bounded by the constraints and objectives identified to be relevant from past projects at Porsche AG, i.e. extended with existing sections in the meta model, e.g. the distinction between *political* and *socio-cultural* constraints had not been made in past processes. Also, predefined elements in the meta model supported completion of the considered scope of constraints and objectives, i.e. articulation of further constraints and objectives remaining implicit after the first articulation attempt (previous section).

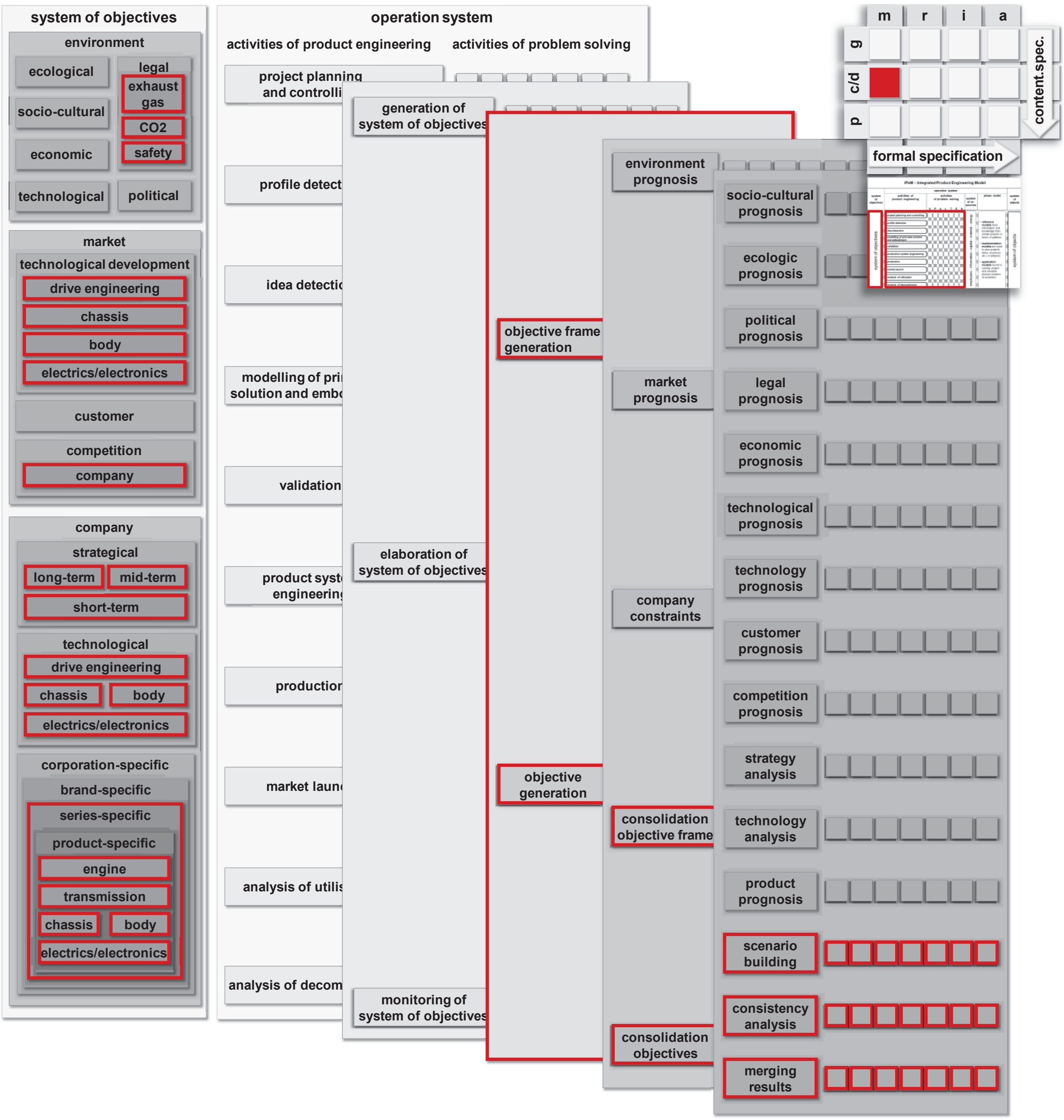

Figure 8-1: Individualisation of the meta model for application at Porsche AG[420]

The second effect was that the necessary additional sections and further abstraction levels for the meta model could be identified (Figure 8-1). For example, the content of the constraints assigned to the section *technological development*, e.g. *trend of hybridisation* and *trend of electrification*, was found to be further distinguishable in superior technologic fields, e.g. *drive engineering.* The same concretised content related sections could be found for the technologies existing as endogenous constraints in the company.

[420] Equivalently as in section 7.3, the icons on the right refer to the specific abstraction level visualised in iPeM. See also the theoretic basics in section 7.3.1 and 7.3.2.

It was also discovered that the actual *production series* of a product needed to be integrated as further abstraction level. This was necessary because there are constraints resulting from e.g. technologies or strategies which might not only be valid for a specific product, but also for the whole brand. An example is the specific motorisation technologies available for implementation in all variants of a Porsche Carrera, but not in a Porsche Cayenne. A further company specific individualisation is the classification of the section *product* into *assembly units*, such as the *engine*. This classification is important during the elaboration of the system of objectives if overall objectives (on product level) are decomposed into assembly units and components. Investigation of elicited constraints revealed that the competition prognosis is segmented into main competing companies of Porsche AG. Their potential future cars are predicted on the basis of constraints effectively assigned to different organisational hierarchical levels of their company. Thus, the additional abstraction level in the section *competition* includes the same section and hierarchy as in their own company.

The individualisation of the activity matrix of the meta model proceeded in a similar manner to the individualisation of the system of objectives. Activities, which had been found to reoccur within several projects at Porsche AG and had been found to deliver an essential contribution to the concretisation and completion of the system of objectives, were compared to the activities predefined in the meta model. In this case, this procedure supported a further articulation of those activities, which had not been previously considered. This is particularly valid for activities carried out due to constraints or objectives which had not been considered until now or were only considered implicitly. These are, for example, *socio-cultural* and *political* constraints and corresponding activities required for their elicitation.

The individualisation of activities to more specific content related abstraction levels on meta level is only useful if respective activities are in fact carried out separately and independently from specific project constraints. A development of the meta model with additional abstraction levels is particularly necessary to distinguish the main macro activities for the development of objectives and their placement in the overall product engineering process in respect to the specific company. In this case, the main distinction necessary is between the activity addressing the *generation of objective frame* and the activity *generation of objectives* (classification of main reference processes). The requirement for a more consistent and holistic derivation of the objectives led to the formulation of distinct activities to regulate and consolidate results for the *objective frame consolidation* and the *objective consolidation* activities. Hence, further activities were necessary on next lower abstraction levels. *Scenario building* depicts activities necessary for developing scenarios as basis for deriving more reliable results (as demanded in the initial requirement for the reorganisation).

The activity *consistency analysis* covers the additional problem solving processes which are necessary to ensure consistency among the distinctly developed results. Finally, the activity *merging results* ensures the reconciliation of these individual results and the generation of a meaningful output.

After modifying the meta model elements to company specific conditions, a suitable naming of the activities and sections in the system of objectives was required. The awarding of a name follows the premises of the general meta model. In addition, an alignment of names of the sections in the system of objectives with activities in the operation system eases a reference between an activity and a corresponding section in the system of objectives, e.g. activity *competition prognosis* with the section *competition*. Naming of model elements was agreed with engineers using the modelling framework to ensure unified understanding and a systematic alignment of mental models of individuals with the formal representation in the framework.

The suitability of the extended and individualised meta model to derive processes for the actual objective generation had been verified through reconciliation with the requirements identified in the second empirical study (section 5.3).

8.2.2 Derivation of the Reference Model

After individualising the general meta model to company specific constraints to describe the system of objectives, respective activities and their interface, a reference pattern for the newly defined process to generate an objective frame was derived. This was done using modelling elements of the individualised meta model and arranging and attributing them in line with previously defined premises. The collocation of activities depended on their best suitable sequence, so that information needed for successive or parallel activities, can be respectively elaborated and provided for those activities in the system of objectives. This is necessary for efficient completion and concretisation of the system of objectives as decision support.

The reference model of the system of objectives was derived by selecting relevant sections from the meta model already known to be needed as clusters to allocate the specific constraints during a specific process execution. Sections were arranged top down, with regard to the element´s content related validity (section 7.4.2). This facilitates identification and visualisation of relationships between sections and incorporated elements. It also ensures availability of already included sections, elements and relationships for sections added later in a specific project. Some sections were further specified according to their content, possible due to specific constraints known for the process *objective frame generation*. For example, the section *legal constraints* could be decomposed into sections *regulations regarding exhaust gas*, *CO_2* and *safety*, not generalisable on meta model level, but for the reference model. For reasons of uniformity, the section *company* in the section *competition* was decomposed into equal hierarchical levels as for their own company.

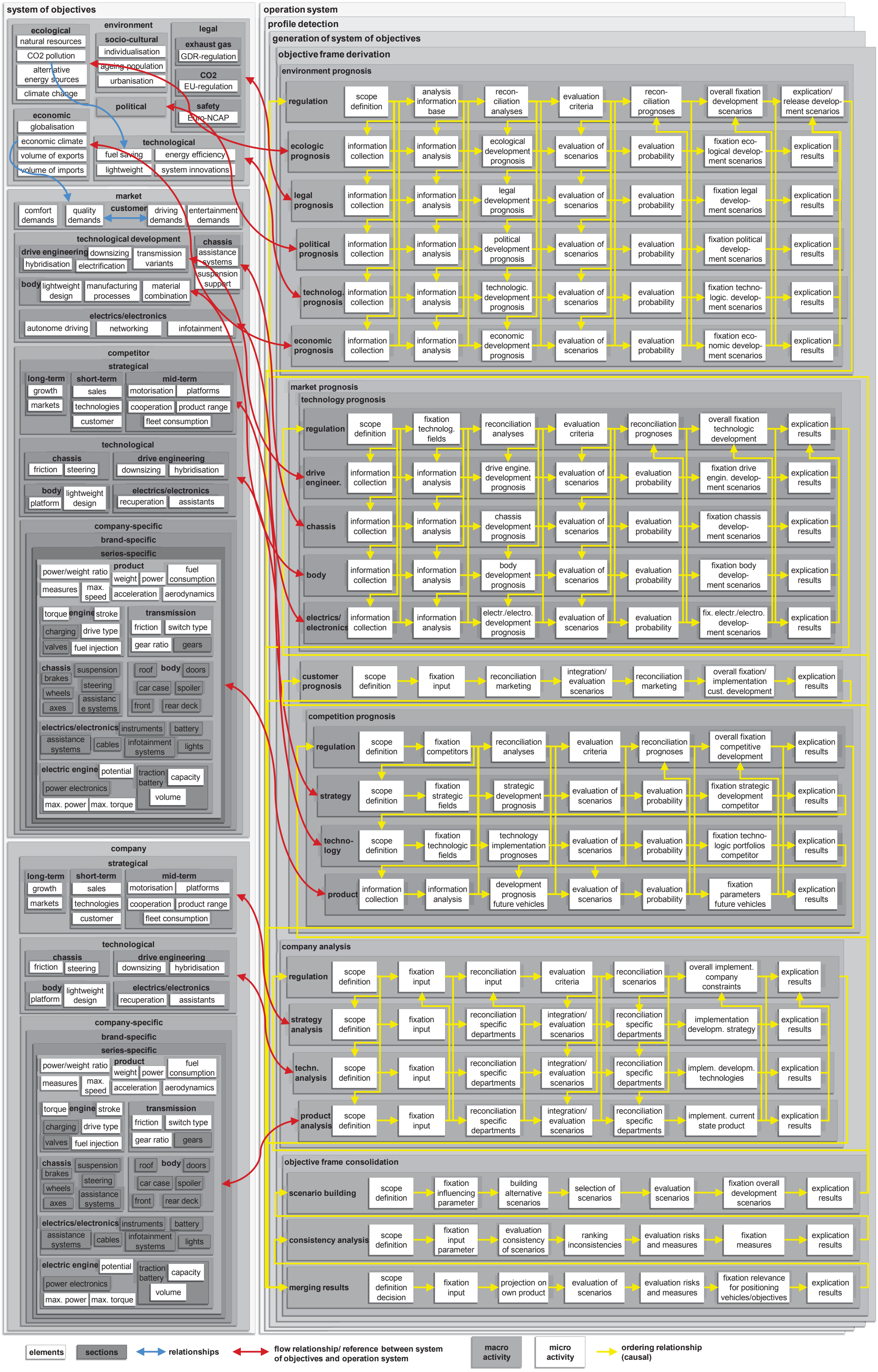

Figure 8-2: Reference model for the process *objective frame derivation*

Constraints and objectives previously identified as reoccurring independent of the project were allocated to their specific sections in the system of objectives, such as the *regulation Euro-NCAP* to the section *safety* constraints, since this regulation applies to any project for which an objective frame is generated. While constraints matched to *technological constraints* as environmental constraints are future potential developments, the section for the technological development of the market also entails elements which may be already available for implementation (e.g. hybridisation). Elements are formally described as project independent (section 6.2.1.1, 7.3.1.2) to ensure adaptability to specific projects, such as the constraint *CO_2-pollution,* which is depicted without further specification, e.g. *CO_2-pollution rises.* Relationships between sections and elements known to be project independent were indicated. These are, e.g. the influence the constraint *CO_2-pollution* has on the technological trend *fuel saving* or the *economic climate* has on the *customer*. As examples show, relationships may be defined for any elements, sections and hierarchical levels. Due to reasons of visualisation the model as shown in Figure 8-2, excludes a number of elements and relationships as included in the complete model.

Equivalently, activities are selected from the meta model and attributed according to premises described above. The visualisation in Figure 8-2 depicts relevant activities from the meta model only once, even if they are executed several times, e.g. by different individuals. This applies for activities similar regarding their content and timely context, such as the competition prognosis, in which the same activities are executed in parallel by different individuals. It does not apply for the execution of activities for an environment prognosis, since they differ in content and timely scope and need to be conducted with an offset to each other due to differences in the generality of their content (e.g. information from ecological prognosis as important information for the prognosis of technological constraints). When referring micro activities, included in the macro activities, to the specific process context it became apparent that the micro activities *selection of solutions*, *analysis of consequences*, *deciding and implementing* as well as *recapitulation and learning* had not been considered as explicit steps in the process as executed until now, but were mostly considered implicitly. Thus, they were explicitly considered in the model. Activities were arranged with regard to their timely sequence, depending on the relevance of their output for succeeding activities to best support completion and concretisation of the system of objectives. Offsets between activities in Figure 8-2 are indicated, but due to visualisation constraints are not representative of the actual value.[421]

[421] A complete visualisation of sequence and timely offset of activities is given in the implementation of the reference model in MS Project in section 8.2.3.1.

Timely or causal relationships are illustrated in Figure 8-2 with arrows. To enable the active control and regulation of the process, as required in section 8.1.3, subactivities of *objective frame consolidation* are recurring activities which link distinct problem solving processes and ensure the quality of the generated system of objectives (*scenario building* → validity, *consistency analysis* → consistency, *merging results* → comparability). The activity *scenario building* refines the basic scenario definition after each activity associated with prognosis, according to new information elaborated in activities. The *consistency analysis* aims to ensure the consistency of results, e.g. by evaluating the coherence of the dependencies between parameters relating to predicted competitors' vehicles. The *merging* of *results* ensures suitable elaboration and provision of information, according to the specific scope of a task, i.e. for a specific decision situation. Also each activity concerned with prognosis contains one activity to regulate other activities and to ensure reconciliation of elaborated content, e.g. the activity *regulation* in competition prognosis ensures validity, consistency and comparability of results elaborated by different individuals. Activities, in which the elicitation of information draws on data from other departments, e.g. legal regulation or customer information, are illustrated. It is not always necessary or helpful to decompose activities down to associated sections in the system of objectives. References between an activity and its associated sections in the system of objectives can also be made between different abstraction levels. A unified formulation of activities, sections and elements was targetted to ease referencing.

8.2.3 Exemplary Supporting Methods and Tools

The basic idea behind the improvement measures was to build upon the existing process environment and to complement it with methods and tools supporting the reduction of uncertainty (section 8.1.3). Thus, as part of the reorganisation measures, suitable further methods and tools had been developed and introduced partly by the author and partly by the employees from the department. This pragmatic approach aimed to link the method and tool environment in a manner to best support the newly defined activitiy workflow and elaboration of results.

The central tool to this approach is a new information and knowledge management database, designed and developed by the author. Its key purpose is to link methods and tools in the process workflow by storing and retrieving information and knowledge centrally.[422] The alignment of its data structure to the structure of the system of objectives, as described in the reference model, enables target oriented elaboration of information and central deposition of the results.

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[422] see for similar approaches Gausemeier et al. 2006, pp. 117

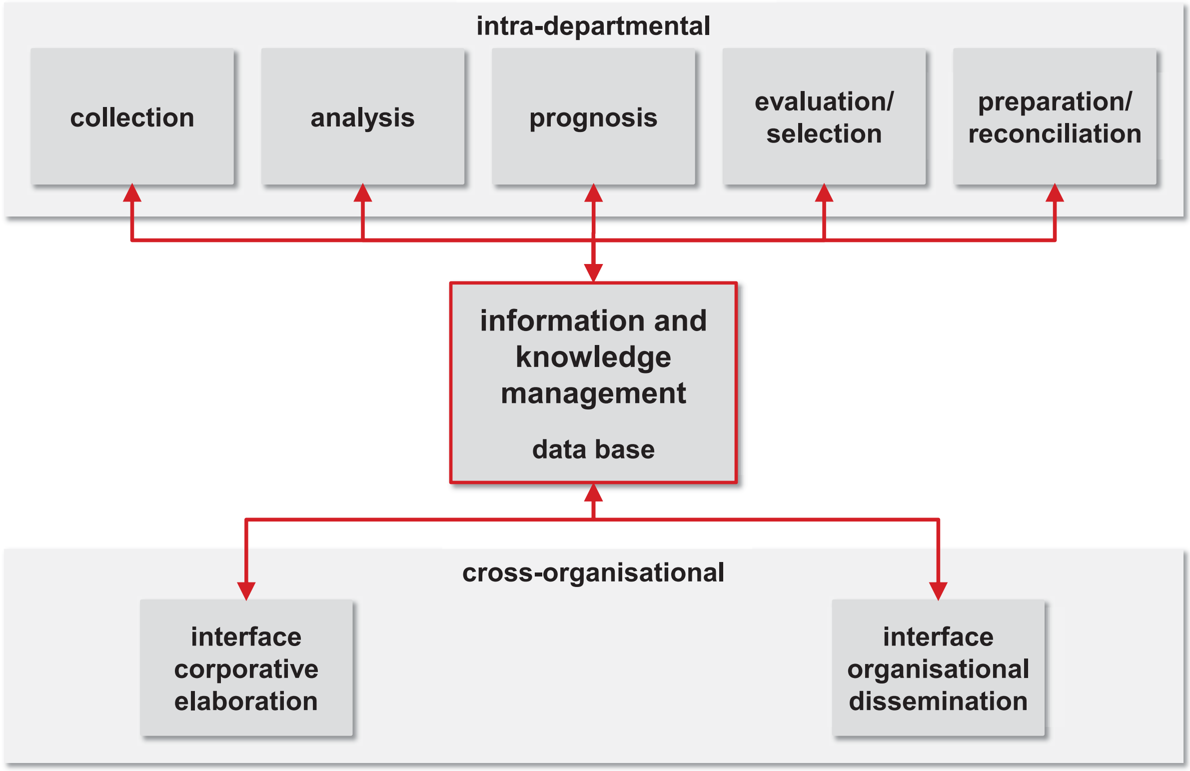

Figure 8-3: Central role of information and knowledge management

Thus, it contributes to reducing uncertainty by ensuring the availability and reliability of information and knowledge. It enables an efficient completion and concretisation of the systems of objectives in one easily accessible tool (Figure 8-3).

8.2.3.1 Depicting the Activity Pattern in MS Project

The commonly available tool that is used at Porsche AG for process planning and management is MS Project. Consequently, this tool has been used to implement the activitiy pattern of the reference model (Figure 8-2), in order to provide the necessary contents and support for operative process planning and management.

Figure 8-4 shows a screenshot of the reference model in MS Project. It can be seen that the left-hand side depicts the different content related abstraction levels of the activities in the reference model. The bottom layer shows the micro activities of the most specified macro activities. The right-hand side also provides an illustration of the activities identified and their relationships e.g. point of start, end (duration) and temporal and causal relationships. Further attributes, such as the number of individuals for each activity, are captured but not shown in this illustration. It can be seen that the identification of activities is done independently of the project, e.g. no exact date for point of start, but a relative arrangement of the activities according to duration (section 7.3.2.2). Thus, the activity pattern of the reference model can be fully described in MS Project and provided for operational use.

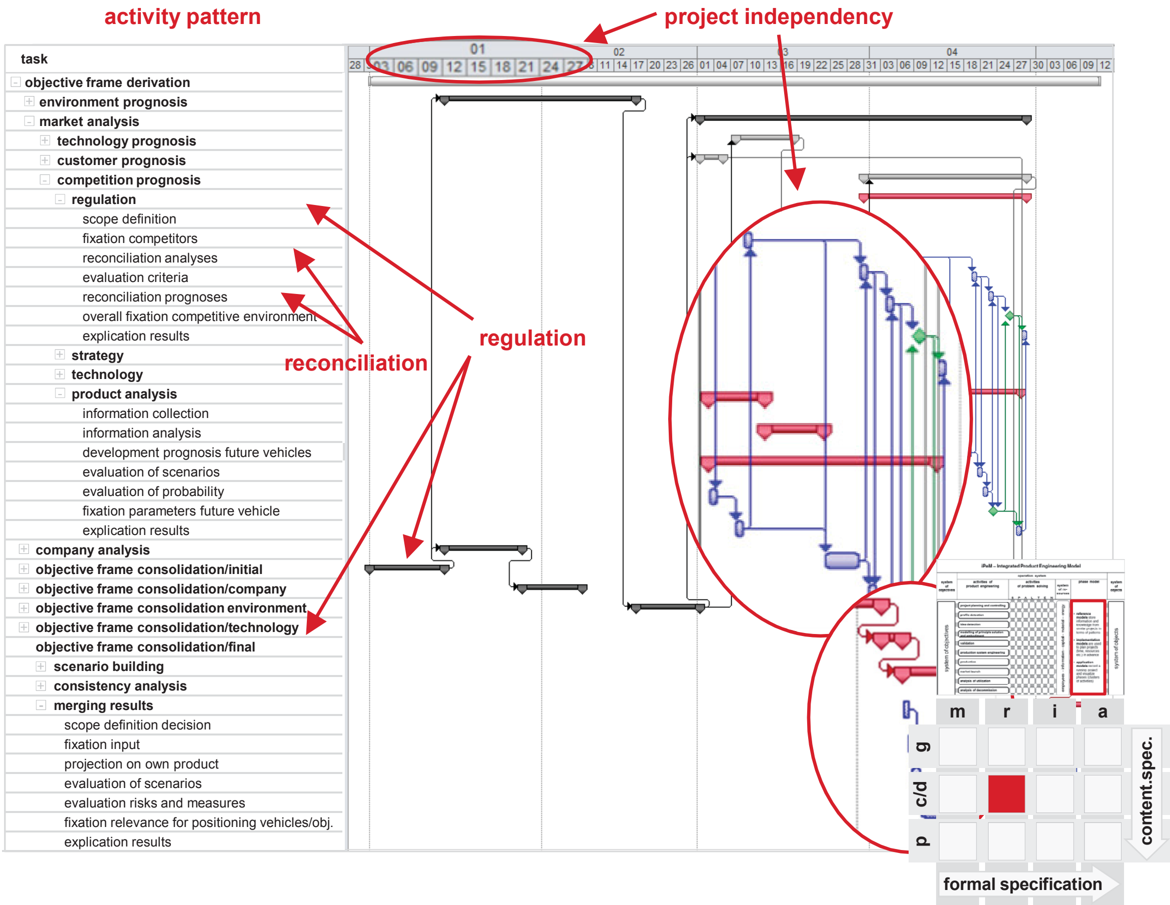

Figure 8-4: Depiction of the reference model in MS Project

8.2.3.2 Depicting the System of Objectives

Besides the common visualisation tools (e.g. MS Power Point, concept maps), there were no available visualisation tools able to comprehensively describe the sections, elements and relationships of the system of objectives as shown in Figure 8-2. Thus, the visualisation (complete version of Figure 8-2) was used as basic visualisation of the system of objectives. This visualisation was taken as a basis to adapt the setup of all tool structures to resemble formulations, arrangement and relationships according to the reference model of the system of objectives (section 8.2.3.5).

8.2.3.3 Defining Scenarios

As outlined, the alignment of the argumentation of prognoses for generating an objective frame was to be supported by defining basic scenarios in order to increase validity and comparability. Due to the limited resources to execute these prognoses and the generation and implementation of scenarios, available scenario techniques were adapted for a pragmatic development of the improvement measures.

The basic scenario for the generation of an objective frame is supposed to be the knowledge from previous projects, as included in the initial system of objectives. Thus, as evident in Figure 8-2, the development of the environment, as identified from the prior projects, is the input scenario for the environment prognoses.

Based on these initial scenarios, the realisation of the environment´s development, as elaborated in succeeding activities, can be used to refine the initial scenarios. Due to the resulting effort, the number of scenarios is in this case usually limited to three. The resulting refined scenarios serve as an input to the definition of the technological development. Input scenarios might be *rising significance of ecology* or *increased mobility demands*. Defining the technological development for both scenarios would result in a scenario not only covering technologies, e.g. for improving fuel efficiency, but also roadmaps showing potential developments of technologies suited to a range of mobility demands.

These refined scenarios serve themselves as input scenarios for predicting future competitor cars. Different developments of the main trends may evoke different strategic decisions by competitors, which may result in differing product ranges and vehicle strategies. Such alternative developments can be described using available scenarios, e.g. competitors might translate main trends into strategies to align their vehicles to be most fuel efficient (original scenario *significance of ecology*), to be more agile by lowering the power to weight ratio through decreasing the weight (original scenario *increased mobility*) or by continuing their present strategy (trend scenario). Since future available technologies differ depending on the scenario assumed, this is to be considered when predicting the development of a competitor´s technology portfolio according to their assumed strategic orientation. Resulting company specific technology portfolios are the basis for predicting the parameters of competitor cars.

Merging the resulting different alternative competitor developments leads to an overview of the anticipated competitive environment, as depicted in Figure 8-10. Applying these scenarios to their own product allows a transparent description and evaluation of alternatives for action in the further development of the product and as a basis for defining their own objectives.

8.2.3.4 Handling of Consistencies in the System of Objectives

A method to support the generation of an objective frame is required to predict parameters relating to future competitor cars, using technological constraints, e.g. a car´s weight. Based on technologies predicted to be implemented by a competitor in a future car (previous section) and their influence on a specific parameter, parameters may be predicted in line with the assumed scenario. The influence of these technologies on a parameter corresponds to the relationship between a technological constraint and a product parameter in the system of objectives (Figure 8-2). Figure 8-5 shows an example of the prediction of an anticipated competitor vehicle.

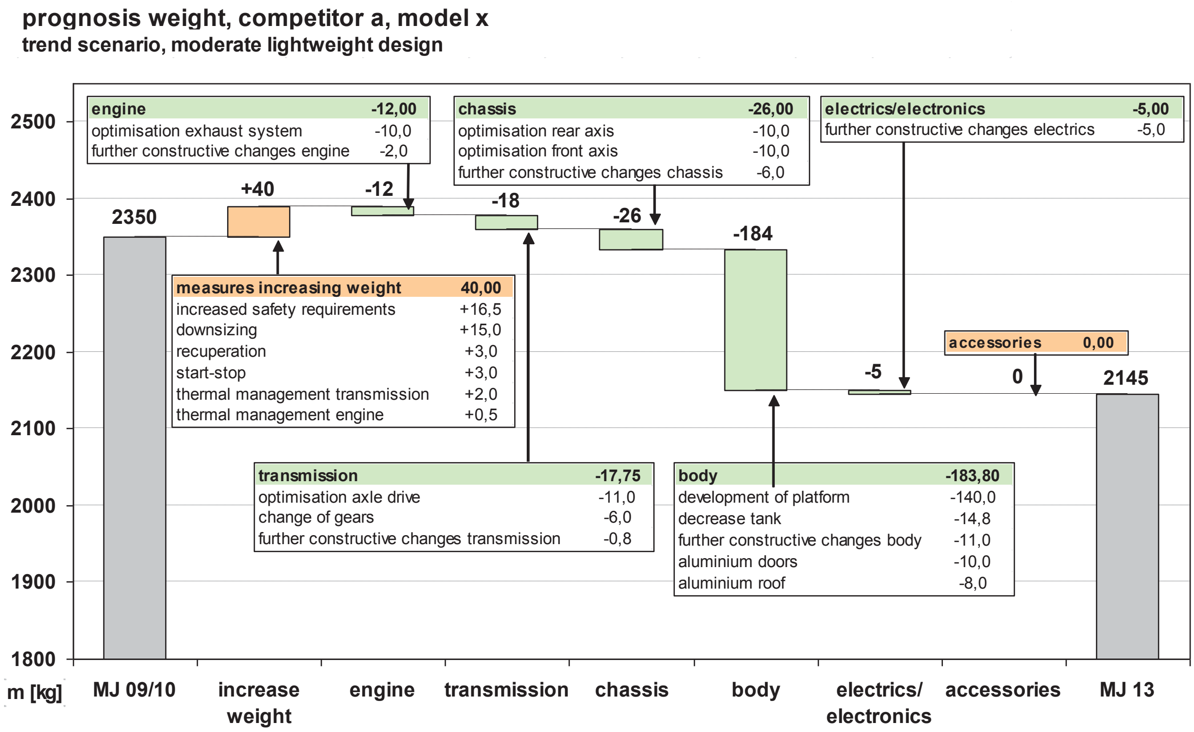

Figure 8-5: Prediction of future competitor car based on technological constraints

Based on the initial weight of its predecessor, the technologies from the anticipated technology portfolio that exert an influence on weight are evaluated to predicted the proposed vehicle's weight. This result becomes more concrete, the more the influence of the technologies on the product parameters is quantified. The extent to which these influences are quantifiable depends on the existing information and knowledge about the technology. Publicly available sources might suggest a weight reduction of a future engine of around 5% with respect to its predecessor, including an allowance for the uncertainty of prediction. Other technologies might be known to experts within their own departments, who might also be able to give estimates. New generations of technologies, e.g. new brakes, may be estimated based on known weights of their predecessors and parts expected to be changed. Since future competitor cars might include changes in construction which influence parameters that are not directly known, these may be accounted for using an estimated overall value (e.g. optimisation axes). There are also explicit calculations that may be used to estimate changes, e.g. in weight, using mathematical equations. This procedure supports the quantification of values, but requires a transparent description of any residual uncertainty.

A tool was developed, based on existing systems for managing objectives, to support the quantified derivation of parameters. It draws existing information on technological constraints for a defined scenario from the central database and returns calculated parameters to the appropriate location in the data structure (according to the underlying structure of the system of objectives).

To handle relationships between parameters describing the concept and dependent parameters, like acceleration time, another tool was developed in the department. This tool bases on a simplified dynamic calculation model, in which relationships between parameters are calculated. These dependencies had been linearised for specific car concepts and parameter values as a basis for a tool with functionality with which predicted concept related parameters and linked technologies can be adjusted or varied and resulting dependent parameters be described in graphs. The database also provides import and export of data of constraints and relationships.[423]

8.2.3.5 Developing Reference Data Structures for Database Support

The basic idea for a tool supporting the handling of information and knowledge in this process was that its data structure describes the reference structure of the system of objectives to facilitate the allocation, storage and provision of information and knowledge processed during the generation of an objective frame. In addition, it should adopt the flexibility of the systemic modelling approach to be able to handle a wide range of sorts of information and relationships in differing projects.

Thus, the concept to define data structures included three different basic structures (Figure 8-6). The *company structure* describes all hierarchical levels of the section *company* in the system of objectives to be able to allocate information directly at the level from which it may be retrieved later, e.g. for analysis. This information is available for all subordinate specification levels by inheritance of the respective data, corresponding to the content related validity of the specific subject (e.g. publications on strategic decisions of a corporation are allocated on the corporate specific level, but are similarly valid for a product specific level). The second structure spans across a company wide unified *product structure*, which describes a parts list of a car on an abstraction level independent from a specific product. This structure is uniform across the company and describes a product *project independent* (reference structure). Actual vehicle parameters are allocated to the respective elements of this list (attributation), e.g. weight on an overall vehicle level, torque of an electric engine respectively for the unit *engine*. They can be attributed *project dependently* before (implementation level) or throughout the course of a project (application level), if the necessary information has been provided or elaborated. The third structure describes the interface to the operative planning of activities within the project, by enabling the definition of projects and allocation of project specific information, like documents, or the creation of suitable reports for a specific decision situation (*project structure*).[424] These fundamental structures constitute the basic frame for each project.

[423] Due to confidentiality reasons, it is not possible to provide a meaningful screenshot of the tool.
[424] There is no screenshot of the project structure in Figure 8-6 for confidentiality reasons.

Technological constraints are reconciled and uniformly implemented in a distinct data area in the database. They are provided as a consistent basis for use in all concrete predictions relating to competitors' vehicles by all contributing individuals. They are assigned to their respective location in the product structure (e.g. *downsizing of engine* to *engine*). All known influences of technologies on product parameters are defined when the technology is generated. This represents the relationship between technologies and parameters (reference level,Figure 8-2). The influence is first quantified, if a technology is actively chosen to be implemented in a certain prediction (project dependent, implementation/application level). This ensures comparability of results but provides the flexibility to specify influences according to present knowledge. Components can be defined as the product units used in various different vehicle implementations, such as engines or transmissions, supporting unification and the reduction of redundancy. The influence of implemented technologies is visible when a product parameter is predicted for a competitor´s model (Figure 8-6). Consistency in prognoses is supported since the existence of influences on all parameters relating to one technology is uniformly defined (this is equally valid for all linked tools, section 8.2.3.4).

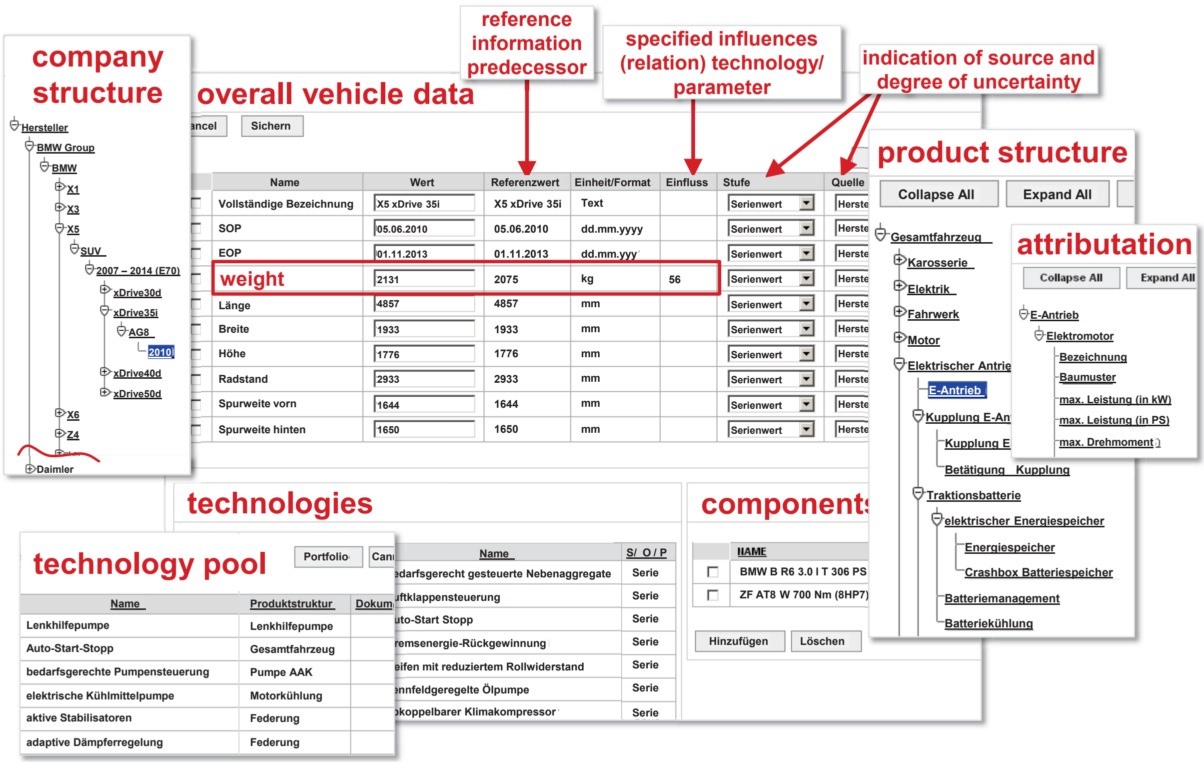

Figure 8-6: Data structures in the database[425]

425 Screenshots are modified due to confidentiality reasons, structures are cut due to original length and important terms are translated (database language is originally German).

The tool also supports the generation of several scenarios for one vehicle model. Any remaining uncertainty can be indicated for each specified product parameter.

The data structures in this database provide a basic, project independent reference structure, which is customisable in response to any project constraints before and during a project (implementation/application structure). Thus, it satisfies the requirements of flexibility and adaptability for suitably describing the development of a systems of objectives, predefined by the fundamental systemic approach. Since it provides the information and its interrelationships for all other tools used in the process, it further ensures that these requirements are met for all the linked tools and thus for all subsequent handling of information.

8.3 Project Application

The restructured process, along with the revised and developed methods and tools, have been applied to a number of specific projects which cannot be described in detail in this thesis due to issues of confidentiality.

Since these projects have taken place in the recent past and respective products have not entered the market yet, an overall assessment of the quality of the generated objective frame, i.e. system of objectives has not yet been made. Hence, the presentation of results obtained with the implemented approach is divided into two parts. Earlier projects lacked explicit project planning and monitoring, and the activities executed cannot be reconstructed. Thus, extracts from project planning and monitoring from a more recent project are outlined to support discussion of the applicability of this research approach to improving the accessibility of the generation of objectives for project management. In addition, the example of a finalised project is revisited (section 2.2 and 6) and used for highlighting the usefulness of this thesis´ findings for improving the quality and handling of a system of objectives.

8.3.1 Project Planning

As described in Chapter 4 and substantiated in Chapter 5 and 6, a suitable support for the generation of objectives needs to be adaptable to specific process constraints. The approach presented in Chapter 7 extended iPeM to specify activities on the levels of abstraction necessary to describe certain processes and provided the means to formally adapt the description to project specific constraints (implementation model). Figure 8-7 shows an extract from a project plan for a specific project derived on the basis of the company specific reference model implemented in MS Project for the process *generation of an objective frame* (Figure 8-4). This illustration shows that the activities and their relationships, as specified in the reference model, could be transferred to a large extent from the reference model to describe the planned activities for the specific project in focus. This saved effort in setting up the process plan.

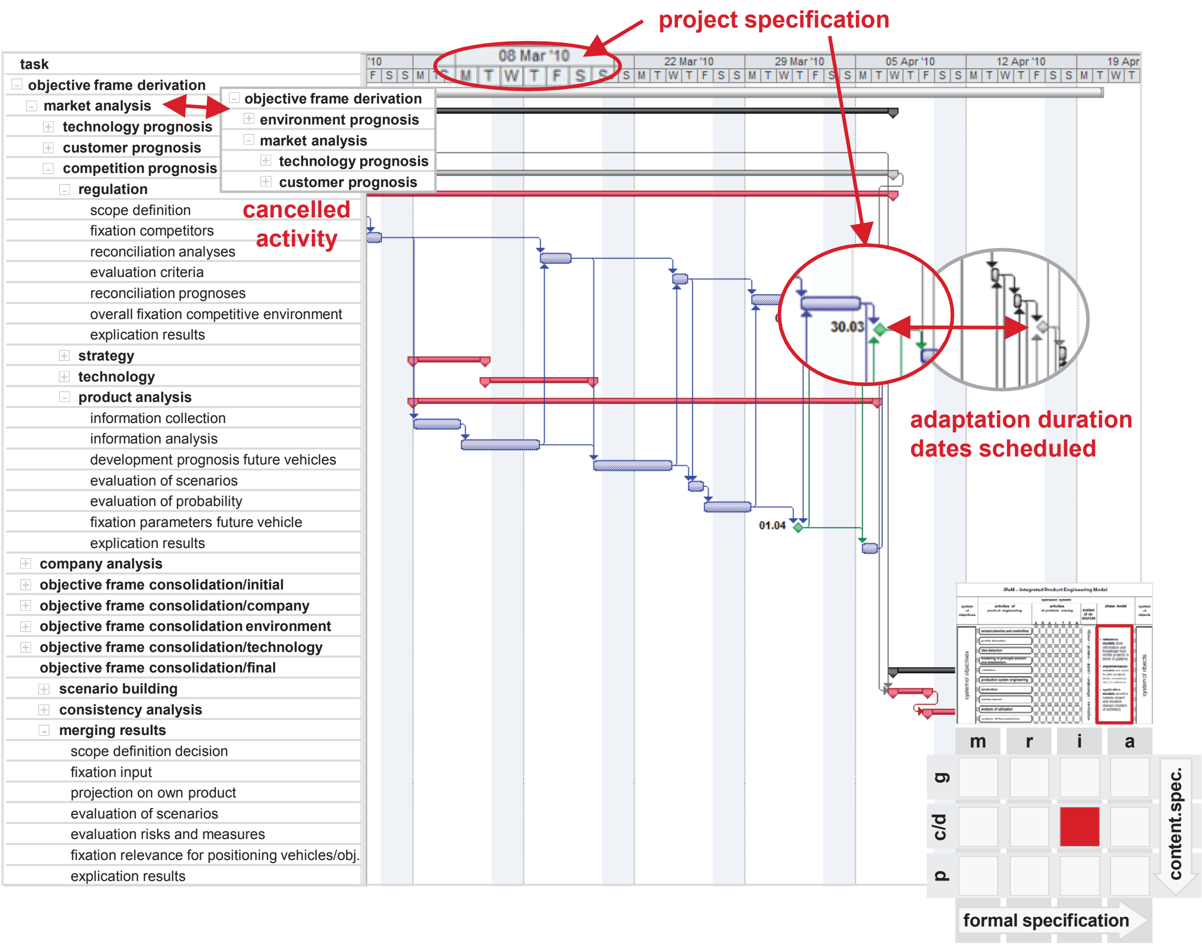

Figure 8-7: Implementation model for a specific project (comparison to reference model)

Only one activity, *environment prognosis*, had been cancelled in this project, since an evaluation had shown that results from a similar project completed just before the start of this project had provided sufficient information for this project´s task.

Regarding the activities shown in the Gantt chart (right side, Figure 8-7), the application of the reference model to the specific project constraints becomes visible in the specified timeline of the project, scheduled milestone dates and estimated duration of activities. This duration had to be adapted for several activities to accommodate the prevailing project constraints, such as for prognosis activities (*development prognosis future vehicle*, *reconciliation prognoses*), since more effort was assumed to be needed for the analysis of competitor´s vehicles. This was due to the novelty of the competitive environment to be researched for this specific project, according to the overall project task, and a correspondingly sparse information and knowledge base.

8.3.2 Initial System of Objectives

The great advantage for reducing uncertainty, by using information and knowledge from systems of objectives of previous projects, had been outlined in past chapters.

An increased availability of such information and knowledge had been also proposed to improve validity, consistency and in particular the comparability of prognoses of the future development of a potential competitive environment. This requirement has been implemented in this approach by installing a central database as single instrument to deposit all information and knowledge, processed throughout the elaboration of a specific project in order to generate an objective frame. Thus, this information is fully available for further use in succeeding projects. Each new project is created in the database as an instance of the underlying reference data structure, which is in itself a copy of the reference structure of the system of objectives (Figure 8-2). Modifications of the reference structure, e.g. additional sections or information already known before project start, can easily be integrated, based on the general rules for building the data structure (implementation structure). As seen in Figure 8-6, parameter values from preceding vehicles can be directly used for comparison with those of future vehicles to be anticipated. Further functionalities, like filtering and search options further ease the decription of the data structure, which represents the implementation model of the system of objectives as basis for a project.

8.3.3 Project Monitoring and Improvement

Insights regarding the development of a system of objectives and respective activities derived in Chapter 6 lead to the requirement that a support approach needs to be adaptable to changing constraints, i.e. additional knowledge and information emerging *during* a specific project. Thus, the modelling approach outlined in Chapter 7 provided the means to track the development of the system of objectives and its respective activities by including inductive project insights in application models.

8.3.3.1 Process Monitoring

Figure 8-8 illustrates an application model created based on the implementation model of a specific project (Figure 8-7). This model had been further refined throughout the execution of the project, by tracking the actual process. It can be seen that the initial activity pattern, as defined in the reference model (section 8.2.2) and used as basic structure for the activities, was extended during process execution. The reason was iteration, which became necessary, since the omission of the environment prognosis in that project resulted in a lack of information and knowledge. This was only recognised at the point in the process when elaborated scenarios where evaluated regarding their probability of occurrence. Consequently, the activities *information collection*, *information analysis*, *development prognosis of future vehicle*, *evaluation of scenarios* and *evaluation of probability* had to be revisited. Even though this and an extended duration of other activities extended overall project duration, uncertainty regarding the lack of knowledge could be made transparent and the overall quality of prognoses could be ensured.

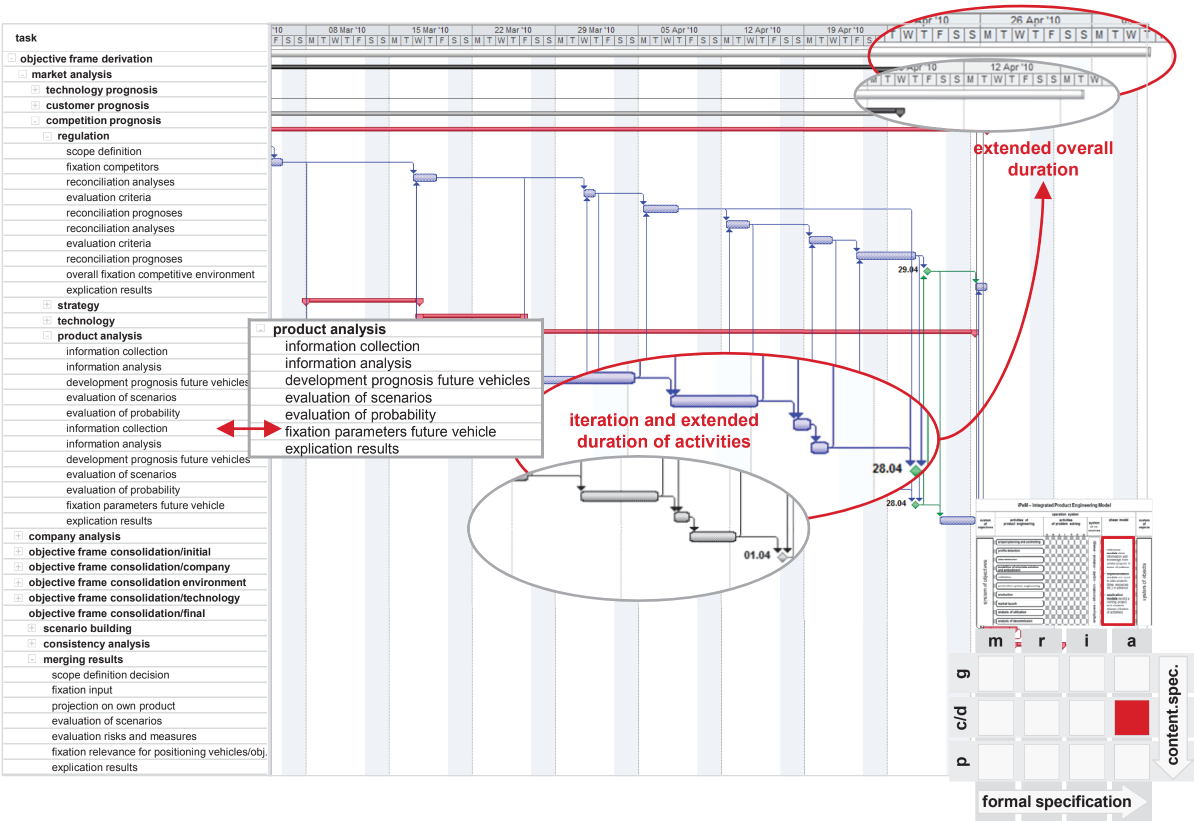

Figure 8-8: Application model for a specific project (comparison to implementation model)

This highlights the advantage of aligning process steps to a basic problem solving procedure, since this procedure requires evaluation of elaborated results regarding risks and opportunities.

8.3.3.2 Final System of Objectives

While the focus of the improvement approach, regarding articulation and modelling of activities during the generation of objectives, was clearly in planning activities more efficiently and enabling control over the execution of activities, the monitoring of the system of objectives *during* its development aims to improve the quality of the results.

In contrast to the comprehensive traceability of the execution of activities in the application model implemented in MS Project, the actual development of the system of objectives as implemented in the database is due to the interconnectedness of the implemented structures hardly depictable. Thus, at first the tool for handling consistencies in the prediction of parameter values, as presented in section 8.2.3.4, is used to outline some of the advantages the improvement approach has accomplished in terms of *consistency* and *comparability*. Then the visualisation of the anticipated competitive environment, as introduced in section 6.1, is used to show the improvements in terms of *validity* of the resulting system of objectives.

Figure 8-9 shows predictions of the parameter values *weight* and *fuel consumption* for one out of four different competitor vehicles for which the complete prognoses had been made (retrospectively) with the information and knowledge from the finished project already described in Chapter 6.

Three scenarios had been defined as a basis (cp. to section 3.1.4.3 and 8.2.3.3) for the predictions: a trend scenario (linear further development of competitor specific strategies), a fuel efficiency scenario (extreme scenario 1) and a lightweight scenario (extreme scenario 2). Regarding the consistency of the resulting anticipated values, Figure 8-9 shows that the procedure used supports the consideration of consistencies. In particular, this comes to light with the conflicting parameters, weight and fuel consumption, which had already been outlined in the introductory chapter.

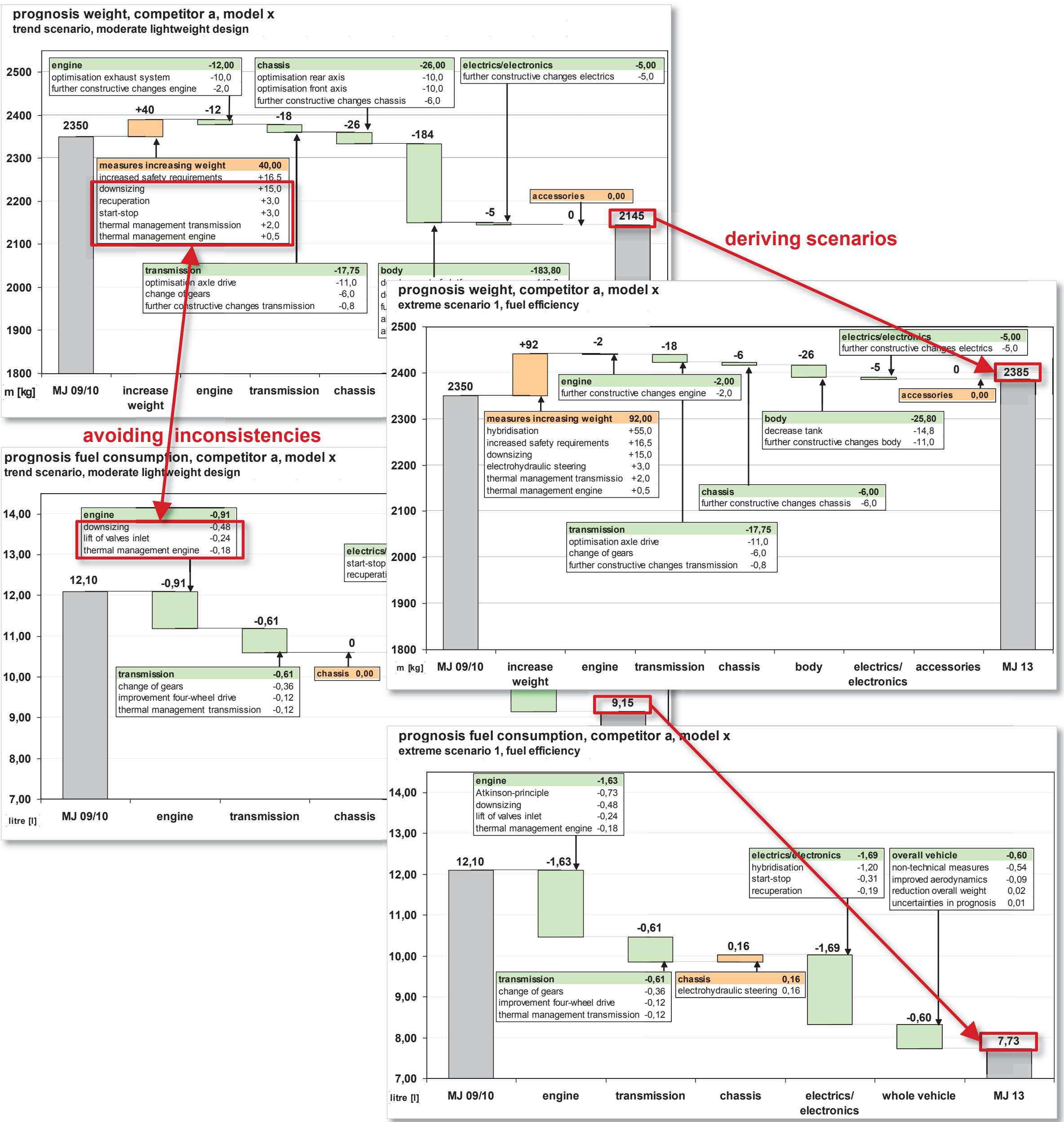

Figure 8-9: Ensuring consistency and comparability in during the generation of prognoses

Figure 8-9 (previous page) clearly highlights that technological constraints, positively influencing fuel consumption, may have an enormous effect on the resulting weight (and associated parameters, such as power to weight ratio, and thus driving performance). This can be seen, in particular, for the second scenario. Regarding comparability, a uniform definition of vehicle parameters and constraints, e.g. technological constraints used, in the database (section 8.2.3.5) fostered the generation of comparable predictions for all competitors. This is particularly relevant to ensure a sufficiently complete consideration of constraints.

Figure 8-10 recalls the illustration which had been used in the introduction of Chapter 6 to derive the relevance of actively using constraints in the generation of objectives, in order to validate the system of objectives and thus to ensure later market success. The multidimensional scaling method was used again to visualise the competitive environment, which would have resulted if the prediction could have been done on the basis of the scenarios as described above.

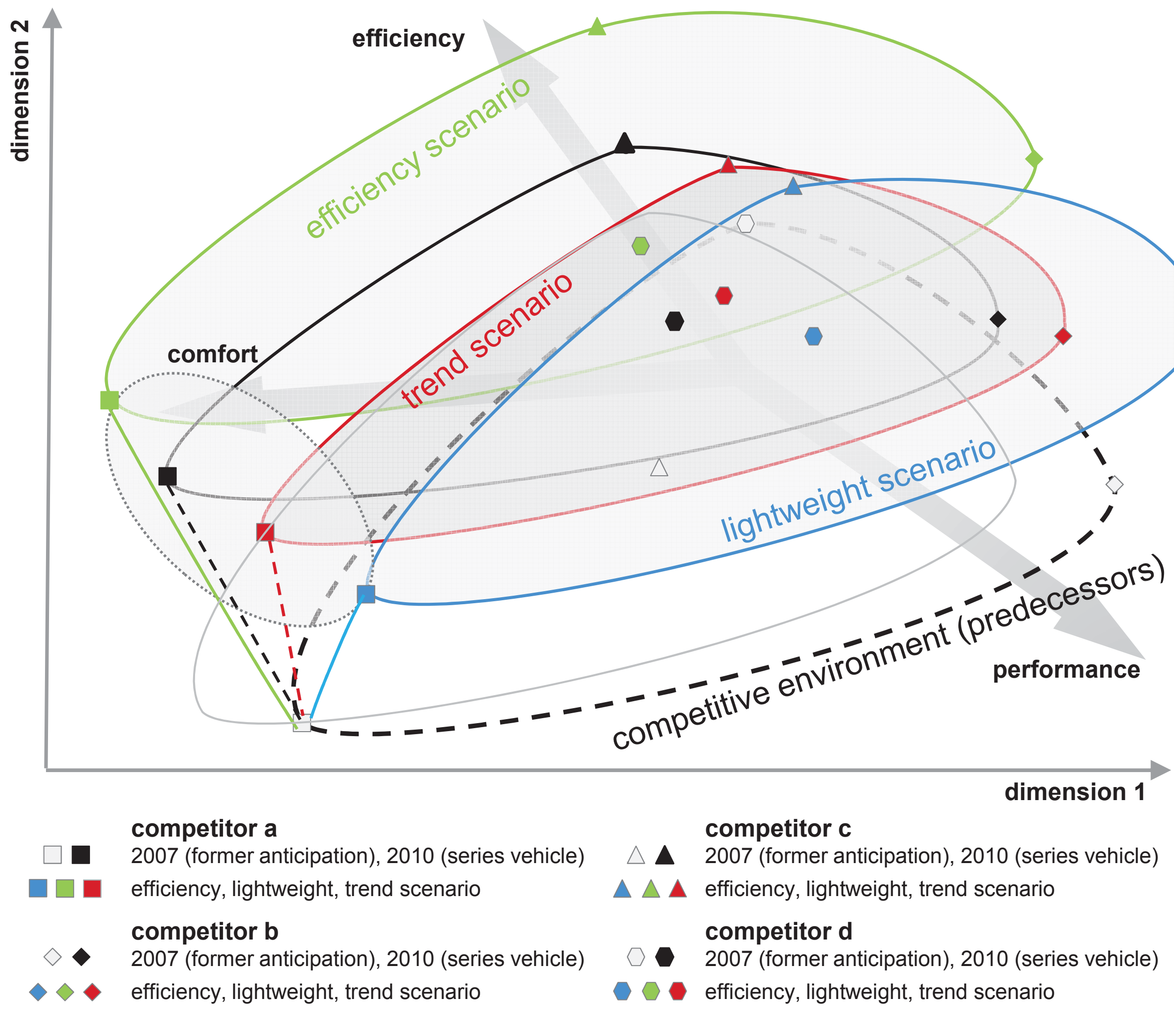

Figure 8-10: Depiction of competitive environment using scenarios

It can be seen that the two extreme scenarios (efficiency and lightweight scenario) and the trend scenario cover most of the area which in fact came to be in reality. Thus, this illustration shows that the use of scenarios, even in a pragmatic way, increases the validity of constraints and consequently may also increase the validity of the systems of objectives, if oriented at the relevant constraints, while transparently describing any remaining uncertainty.

8.4 Insights

This chapter aimed to outline the applicability of this thesis´ approach to a practical environment and to verify its suitability in making the consideration of constraints in the specification of objectives transparent and accessible to operative management. The first part of this section described the specification of the theoretical approach from Chapter 6 and 7 to the specific constraints of the company which had been studied before (Chapter 5). This environment was perfectly suited to demonstrate the adequacy of this approach to contribute to the problem initially specified in the introduction. This verification can be divided into two parts: first, the verification of the ability to model and manage the actual process for the generation of objectives; and second, the verification of the ability to model the system of objectives and to improve its quality during its generation.

The example showed that the approach, based on the modelling framework of iPeM along with the possibility to define activities on problem specific classification levels, is suitable to describe and structure real world processes on an operative work level. Previously implicit activities could be made transparent using the formal language of the meta model, which could be directly tailored to company specific constraints. Reference models, serving to assemble the elements of the meta model, need to be defined only once and thus reduce the effort necessary for process planning. Despite this basic structure, these models are still flexible enough to be customised to specific process constraints and be improved by conveying insights gained in the process execution inductively back into the basic reference model. The modelling framework enables the arrangement of the activities in an order which supports the elaboration and provision of results best suitable for concretising and completing the system of objectives for specific decision situations.

The modelling approach proved that the system of objectives can provide a basic structure to support the quality and completeness of the system, while being able to adapt and extend it throughout the whole project with tools supporting information and knowledge management. It does support a unified, transparent, valid, comparable, consistent and complete development of the contents of the system of objectives, in particular, by providing the right information at the right point in time.

Enforcing a reduction of uncertainty by consistently linking and arguing intermediate results based on different potential scenarios, supports the validity and consideration of constraints in the generation of objectives.

Embedded in the reorganisation process, the application of this thesis´ approach contributed to increased transparency, relevance and consideration of constraints in objectives. After several process executions with an increase in quality of results aligned with the transparent handling of uncertainty provided by the objective framework, the acceptance of the results in the organisation at Porsche AG has further increased.

9 Conclusions and Further Work

This thesis has discussed objectives in a complex engineering environment in terms of setting guidelines on how product engineering needs to proceed to accomplish a chosen task based on valid objectives. The issue of valid objectives, however, is ubiquitous. In fact, everyone is continually facing the challenge to generate valid objectives for their own daily life. Take the elaboration of research objectives for this thesis as example. A complete, well argued research project could have been undertaken on virtually any issue one can think of, but in the end, its contribution for research depends on whether somebody else might already have published similar thoughts or whether the subject in focus is relevant for current research questions. Industry will only adopt results if they contribute added value to burning issues and are easy to implement. In other words, if a research project is not sufficiently aligned to present constraints from research and practice, its results may be inappropriate and not applicable. If such constraints are taken into account, it is nonetheless crucial to consider *relevant* literature and choose an adequate industrial background as valid constraints. Finally, a thorough definition of research objectives with a suitable scope will significantly influence the quality of elaborated solution approaches.

Related to the generation of objectives for the development of new products, this issue had been similarly identified and was tackled in this thesis in two parts:

- Which problems occur during the generation of technical objectives and their alignment to relevant constraints?
- How can such problems be overcome, i.e. valid technical objectives be generated whilst maintaining alignment to relevant constraints?

This section evaluates answers to these issues, thus to the defined research questions, as worked out in this thesis. It argues that this thesis does indeed contribute to the state of the art in research and satisfies current needs in practice, since its research objectives were sufficiently defined and refined based on constraints from literature and practice and the research approach was constantly validated against the objectives and verified in its final application environment.

9.1 Core Conclusions

The main insight revealed in this thesis was that problems impeding the generation of objectives are mainly caused by a lack of perception of the importance of the generation of objectives, including their alignment to relevant constraints as a coherent and explicit process.

Since associated activities are primarily executed in early engineering stages, high prevailing uncertainty and several other factors, such as methods used, information handled and individuals responsible have a significant influence on quality and utility of developed objectives. Thus it was concluded that an improvement the generation of valid objectives, pertinent constraints, can only be achieved, if handled objectives, constraints,their coherence, and all contributing process elements, are made sufficiently explicit. This is a key condition to be able to access this process and make it manageable. Its improvement can be achieved by actively using the factors influencing this process to control and minimise uncertainty. Hereby, flexible support is necessary to model, handle and increase efficiency of the process. It was concluded that such a support can be realised by using a modelling framework as the integrated product engineering model (iPeM) by ALBERS, since it is based on systemic principles and provides the necessary mental models to depict the development of systems of objectives comprehensively and situation specifically.

Table 9-1: Further conclusions elaborated in this thesis

holistic perspective	Chapter 3	→ distinct research fields tackle aspects (e.g. early stages, uncertainty, problem solving), but lack an encompassing perspective on the issue → causes for insufficient consideration of constraints in technical objectives are not holistically addressed, improvement approaches are not provided
number of constraints	Chapter 5	→ rising requirements and need to persist on the market, forces industry to improve the alignment of products to demands of market and environment
uncertainty	Chapter 5	→ handled constraints are characterised by a high state of uncertainty, since they represent a future state, anticipated in the early engineering stage
relevance	Chapter 6	→ insufficiently considering constraints in objectives can support a misplacing of the product on the market, thus constraints serve as a validation of the objectives, whereas the objectives serve as validation for the product
systemic understanding	Chapter 6	→ constraints and objectives can be described by the same characteristics and are strongly interrelated, thus they need to be treated as system → the state of a system of objectives can be described by its degree of completion, concreteness and quality (validity, consistency, comparability)
development	Chapter 6	→ since objectives and decisions as part of problem solving are contingent, the generation of objectives can be represented as a problem solving process → the progress of a system of objectives´ development equals a reduction of its inherent uncertainty by completing and concretising the system´s content → influencing factors affect the extent to which uncertainty can be reduced
handling	Chapter 6	→ processes, methods, tools, used information and contributing individuals are actively amenable to improve the integration of constraints in objectives → the inherent aleatory uncertainty of the constraints can only be dealt with by providing flexible (adaptable) support of the process
modelling	Chapter 7	→ iPeM provides the necessary systemic basis and mental models to depict the interface between systems of objectives and the operation system → using different levels of abstraction, iPeM can visualise the interface for different purposes and accounts for a dynamic development of objectives

9.2 Contributions to Research and Practice

The main contributions of this thesis for research and practice can be summarised:

- insights regarding the generation of technical objectives and their alignment to relevant constraints as well as potential ways to improve the process
- provision of an approach to access and support the generation of technical objectives for operational management and improvement

Evaluating the results of this thesis in the context of related research fields associated with the issues addressed (Figure 1-3), this research work provides the first review of current literature discussing the generation of technical product objectives with a focus on the role of future product constraints (Chapter 3). Since previous research has not sufficiently investigated the significance of this issue, empirical results presented in this thesis provide a first in-depth study of industrial processes related to this issue and an evaluation of its relevance for industry. In addition, an analysis of the relevance of objectives for product engineering highlighted the importance of research on this issue. The elaboration of a detailed understanding of how objectives and constraints can be perceived as explicit and implicit and linked in an overall system, opens up a new perspective to address objectives. This new perspective is complemented by enabling access and improvement of the development of objectives by its representation as a problem solving process. These insights are in particular crucial for the early engineering stages which are as yet not sufficiently researched and supported. Using a holistic systemic framework to model the generation of objectives in its respective engineering context constitutes the first approach to open up this process to operative situation specific management.

The main contribution to practice is the creation of awareness of the relevance of a valid system of objectives for product success and that its generation represents a coherent process, affording a holistic view on contributing activities, methods and tools as well as the handling of objectives and constraints. This thesis further contributes to an increase of knowledge on how this process may actually be managed. Finally, its provision of a basic methodology, implementable in an existing process environment, supports the operational handling and management of the generation of objectives and thus contributes to making the process more efficient. This approach assists in improving the alignment and quality of objectives for designated decision situations, based on knowledge on influencing factors and a customised modelling approach.

9.3 Evaluation of Research Questions and Hypotheses

Based on the review of current literature regarding the initial problem specification, several research hypotheses and resulting research questions had been formulated in Chapter 4. The elaborated answers are summarised.

> **Research Hypothesis 1**
>
> Technical objectives are generated by activities, which are carried out mainly implicitly by different involved individuals with little central regulation. This impedes an active and efficient support of this process.
>
> **Research Question 1 (→ Chapter 5)**
>
> How are technical product objectives generated, how are constraints from market, product environment and the own company considered and which factors influence this process?

The approach of this thesis is rooted in a broad empirical study, carried out in a three-year research collaboration with Porsche AG, to understand how technical objectives are generated in industry and which obstacles challenge this process.

It was found that activities to generate objectives are only partially linked to official product engineering processes by roughly defined intermediate results for important product decisions, e.g. on product concept. Objectives are derived differently by different departments with little reconciliation and perception of objectives as part of an overall, interlinked system. The extent to which constraints from a future product environment are considered in objectives depends on specific individuals. Further factors perceived to be responsible for the low level of standardisation in this process are the prevailing uncertainty in this early engineering stage and constraints changing between projects.

Due to an insufficient understanding of handled objectives, interrelated constraints, respective activities and perhaps also an underestimation of the relevance of valid objectives for later product success, there is little active planning and management of this process and few adequate support methods and tools.

> **Research Hypothesis 2**
>
> The development of objectives and the way and extent to which constraints are considered depends on various influencing factors and their interdependencies.
>
> **Research Question 2 (→ Chapter 6)**
>
> Which factors influence the development of objectives and in what way?

The analysis of engineering projects at Porsche AG revealed that constraints represent an important means to validate objectives in the context of an anticipated future product in an anticipated future product environment. Thus, the research on the development of objectives was necessarily based on a definition of a system of objectives which includes implicit as well as explicit constraints, objectives and their relationships. Using steps of problem solving processes as abstracted steps in the generation of a system of objectives, it was shown that the development of a system of objectives can be equally described by its reduction of uncertainty.

The validity, consistency and comparability of the system of objectives are strongly influenced by the implicit and explicit models an individual uses for each step in its generation. Depending on how systematically the individual proceeds, the prior knowledge he owns and methods and tools he chooses, more or less uncertainty can be reduced in the development of a (partly implicit) model of a system of objectives. Unforeseeable aleatory uncertainty may influence the system of objectives negatively or positively.

Research Hypothesis 3

The development of improved objectives can be achieved by actively manipulating the influencing factors.

Research Question 3 (→ Chapter 6)

Which of the factors can be influenced and in what way?

Activities, methods, tools as well as information handled and individuals contributing to the process can be actively influenced. This can only be done if they are explicit and known. The extent to which an adaptation of these factors can be used to reduce uncertainty depends on their content and degree of standardisation (activities, methods, tools) as well as availability, measurability, reliability of information and prior knowledge and systematic procedures of individuals.

Thus, e.g. activities can be aligned to best support the consistent generation of results. Those methods may be used for which underlying models are best suited to a valid prediction of future constraints. Tools and information can be targetted at increasing the availability of information. Standardisation of these process elements improves quality and efficiency in generated objectives, but needs to be sufficiently flexible to handle changing constraints or other aleatory uncertainty which may influence the process.

Research Hypothesis 4

The development of objectives can be made explicit by using the systemic modelling framework of iPeM, making the process more accessible to active improvement and management.

Research Question 4 (→ Chapter 7)

How can the development of systems of objectives be made explicit and thus manageable and improvable for operative use within the modelling framework of iPeM?

To be able to elicit and model the development of systems of objectives on a standardised but flexible basis, the iPeM modelling framework had to be extended with regard to its abstraction levels and systemic description of the system of objectives and operation system. By being able to describe objectives, constraints and their relationships, as well as respective activities on different abstraction levels, a situation specific modelling of their interface, necessary for depicting the generation of objectives, can be achieved. This modelling framework provides a basic set of elements, specifiable for processes in an operational work environment.

Summarising the insights, the approach of this thesis answered the research questions set and thus was able to fulfil the desired research aim.

Research Aim

- Identification of factors which inhibit the generation of objectives on the basis of relevant exogenous and endogenous constraints.
- Development of an approach based on iPeM to make the generation of objectives accessible to operative management and improvement.

The additional requirements defined in Chapter 4 were fulfilled as follows:

- *set theoretic basis*: analysis/definition of relevance, contents and development of systems of objectives under the consideration of relevant influencing factors
- *ensure applicability in practice*: verification of the approach by application in the industrial environment used for the initial empirical studies
- *support systematisation, standardisation, transparency*: a common language for process elements in the meta model supports comparability and consistency
- *flexible adaptation, customisability*: models of operation system and system of objectives can adapt to changing project constraints before and during projects
- *increase efficiency*: the approach enables efficient control of the execution of activities and requires little effort in deriving situation specific process models
- *basis for further research*: see subsequent section 9.5

9.4 Limitations of this Research Work

This thesis has investigated objectives in an engineering context from a specific perspective. A focus was laid on investigating the generation of technical objectives in the early engineering stages by using empirical studies from the automotive industry as an example. It aimed to identify deficiencies in the process and to provide general strategies for their resolution. This defines the scope of this research.

9.4.1 Generalisability

Empirical findings of this thesis cover one company in the automotive sector. Even though thorough research could be undertaken due to the long duration of the research collaboration and findings were generalised from company specific methods and tools, a complete transferability to other companies or departments can only be estimated. Also the focus during the elaboration of theory regarding the development of systems of objectives was on the early engineering stages and insights gained could not be verified for later development stages due to the scope of this thesis. However, the systemic description of the approach opens up the opportunity to further generalise the approach to other domains. It is assumed that it holds great potential especially for interdisciplinary development environments. Challenges will probably arise in ensuring that elements of the basic meta model will remain redundancy-free. Further challenges may be given by the application to different organisational structures of different companies and branches.

9.4.2 Methodology

The theory developed included the postulations that the use of different methods and tools has an influence on the reduction of uncertainty and gave recommendations on the type of methods and tools suitable for this process. Due to the scope of this thesis, it did not include an explicit discussion and evaluation of specific suitable methods and tools. The elaborations focused on providing a basic strategy for complying with the developed theory to improve the deficiencies identified. The modelling approach does not cover an explicit assignment of methods and tools to respective activities and their inclusion in the systemic modelling approach.

9.4.3 Applicability

In particular, Figure 8-2 (Chapter 8) highlighted advantages of the systemic approach to structure objectives, constraints, activities and their relationships, but also revealed the emerging complexity in the system of objectives and operation system. This complexity is due to the high number of elements and relationships, resulting when targetting a complete and situation specific description of the system of objectives and the operation system.

Hence the visualisations presented only described an extract of the complete number of elements due to a lack of suitable visualisation tools. In particular, in the operation system, the situation-specificity is improved but also the complexity rises hugely the more abstraction levels, i.e. subactivities are modelled. Modelling second and third abstraction level of the problem solving cycle (section 7.4.1.2) for all macro activities and subactivities in the proposed meta model and in derived models is nearly impossible with reasonable effort.

The applicability of the basic strategy and structuring methodology is assumed for any environment, but has until now only been verified in one process environment (Porsche AG). It is estimated that the approach will be especially helpful for companies, working on highly complex products with multiple and interrelated constraints, such as for example the aerospace industry. Challenges will be the mentioned handling of the complexity of the product and its constraints for different types of products and in different brances. Furthermore, it is yet not fully known, how intuitively individuals from different organisations will be able to apply the approach.

9.4.4 Cost and Benefit

The approach in this thesis as presented in Chapter 6 and 7, forms a framework, customisable and implementable in different industrial environments. Taking the application of the approach at the Porsche AG as example, the overall procedure of identifying the as-is state (Chapter 5) as well as tailoring the modelling approach to the specific environment took the author about three months. This procedure is to be done only once to customise the approach for a specific organisation and to provide it for an application to different projects in that organisation. Its application to a specific project has turned out to be feasible in parallel with regular project planning activities and thus does not cause further effort. The direct benefit, which has been perceived from engineers at the Porsche AG concerned with the development of objectives, respectively their constraints, is that they were able to conduct their work more target-orientedly and efficiently due to higher transparency and structure of their activities and results. Consequently, the application of the approach supports to shorten the duration of early stages in a development project and thus saves cost intensive development time. The indirect benefit, yet difficult to be measured, is the assumed improvement of actual sales of the resulting product due to its increased suitability to future constraints. The approach is especially helpful and worth spending the necessary cost for implementation for industrial environments working on complex products with a lot of interdependent constraints to be taken into account. Companies developing products with clearly defined objectives and constraints may not be able to fully benefit of the advantages of the approach, such as its support for structuring according activities and constraints.

9.5 Further Work

This research work is one of the first explicitly focussed on the investigation of systems of objectives.[426] The potential of systems of objectives, as outlined in section 6.1, for aligning new product concepts to future product environments and to ensure a target oriented internal product development is only gradually being explored by academia and industry. Thus, to expand the knowledge about the handling of objectives in the later development stages, it is essential to undertake further empirical studies in different companies and further departments, which may also be exposed to characteristically different constraints. The elaborated theoretical postulations need to be verified regarding their generisability to later engineering stages, especially for the detailed elaboration of elements of systems of objectives (second characteristic stage, section 6.3.2).

Currently, further research effort is being spent on handling emerging conflicts in a system of objectives, which is accompanied by another extensive empirical study in a different industrial branch. Another important aspect of the system of objectives, which had arisen during the execution of the empirical study in this thesis, was its role in motivating individuals contributing to the engineering process. The study had shown cases in which the formulation of an ambitious objective encouraged greater effort and thus led to results, even thought it was perceived initially as unachievable due to insolvable objective conflicts. Further potential to complement the results of this thesis is to evaluate and develop further suitable methods for directly reducing uncertainty in the system of objectives. Also, an approach to match methods and tools to respective activities in the modelling framework would be reasonable.

Further research efforts, in particular, regarding the operation system need to focus on the reduction of complexity for increasing its applicability. Current research regarding the further improvement of the utility of iPeM is focussed on empirical studies in several student´s research projects at the IPEK.[427] Finally, the modelling framework needs to be applied to different process environments to constantly improve its applicability.

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[426] for a related work, see also Oerding 2009

[427] see, for example, Albers & Braun 2011, Albers et al. 2010a

9.6 Summary

A quote of HALL, one of the founders of systems engineering, reveals that the issue discussed in this thesis is basically not new, but has not yet been sufficiently addressed:

> *"There is no unique path to a good set of objectives. […]. The lack of a comprehensive approach to setting objectives is no excuse for not facing up to the problems of setting them. Neither does this lack justify the arbitrariness, imposition, dogmatism and absence of logical thought so frequently found in work on objectives."*[428]

This research work has addressed this claim by providing insights on issues impeding the generation (setting) of objectives and proposing a comprehensive approach for its improved execution. The approach provides basic guidelines, while allowing for flexiblility in reacting to unforeseen changes in the early engineering stages. Positive feedback from responsible individuals gained during its application in a practical environment confirmed the suitability of the concept and has encouraged further research in this field.

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[428] cp. to Hall 1962, p. 108

A Appendix

A.1 Content Related Additions

A.1.1 Methodology

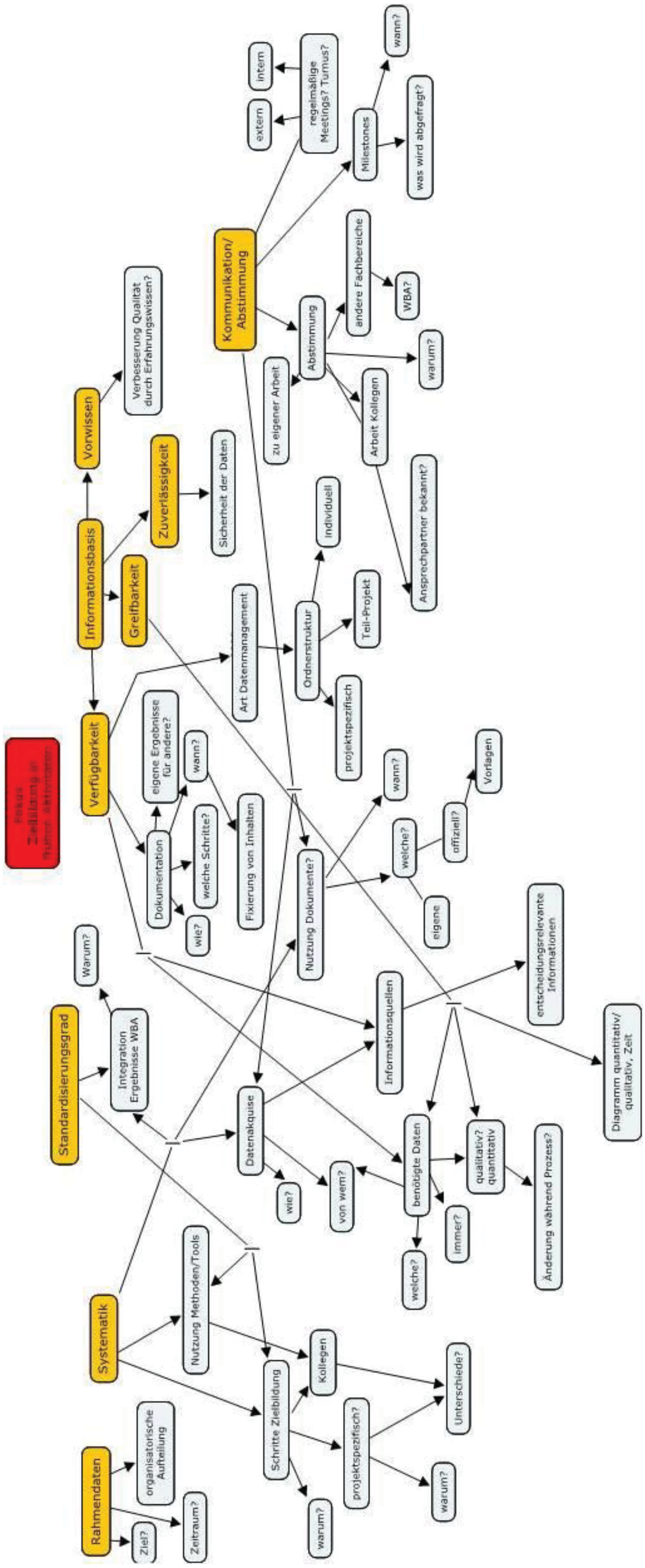
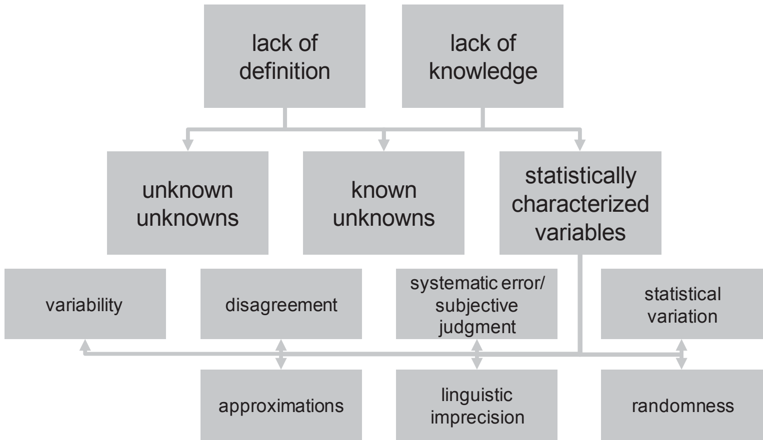


Figure A-1: Concept map as basis for interviews (section 2.1, 5.3)

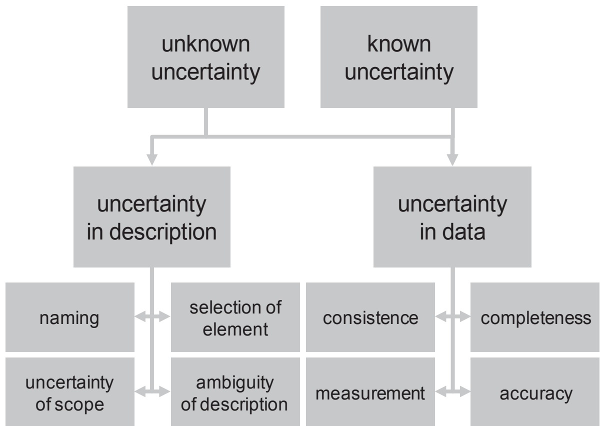
A.1.2 State of the Art

Table A-1: Selected classifications of uncertainty (section 3.1.4.2)

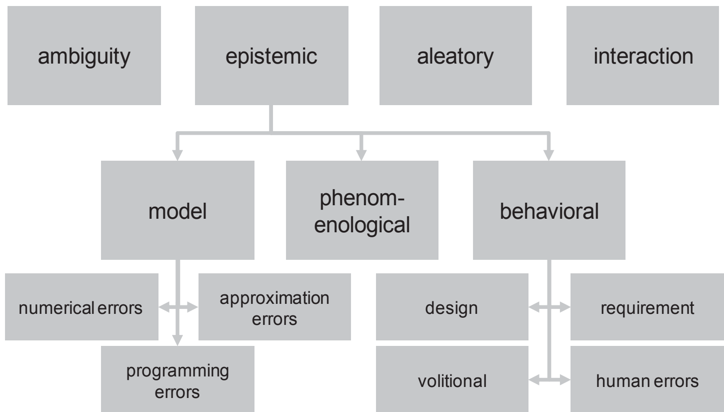
HASTINGS[429]



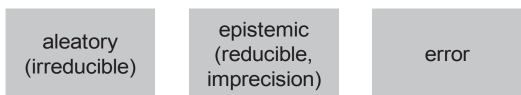
EARL ET AL.[430]



THUNNISSEN[431]



CHALUPNIK ET AL.[432]



[429] Hastings & McManus 2004, pp.3
[430] Earl et al. 2005, pp. 182
[431] Thunnissen 2005, pp. 36
[432] Chalupnik et al. 2009, p. 463

Table A-2: Imperfect information (section 3.1.5.3)[433]

Imprecision	
vagueness	
ambiguous	has several meanings
approximate	decidable if information is correct or not
vague	not well defined
fuzzy	decidability lost with fuzzy information
missing	
incomplete, deficient	something missing
erroneous/incorrect	just wrong
inaccurate	imprecise, but not completely erroneous
invalid	based on a mistake, would lead to unacceptable conclusions
distorted	meaning different and misrepresenting what it should be
biased	tainted by a systematic/constant error
nonsensical, meaningless	without sense, without meaning
inconsistency	
conflicting	disagreement among the data, not compatible
incoherent	unclear, rambling in reasoning
inconsistent	not constant to the same principles of thought or action
confused	no order or pattern
uncertainty	.
objective	Property of the information, external uncertainty
propensity	
random	subject to change
likely	will probably occur
disposition	
possible	ability to occur, to be true
necessary	negation is impossible, not possible
subjective	
believable, probable	observer accepts the data to be likely, but is ready to reconsider it
doubtful	observer can hardly accept the data (unlikely/uncertain)
possible	observer's considers that the data could be true
unreliable	observer opinion about the source of the data, not trustable
irrelevant	observer doesn't care about the data, not relevant to focus
undecidable	inability to decide if true or false

[433] cp. to Smets 1997, pp. 228, 245

A.1.3 Multidimensional Scaling

Multidimensional scaling (MDS) describes a characteristic type of data analysis procedures in multivariant statistics for visualising similarities. The aim is to describe objects in a multidimensional space in such a way as that the distance between two points in this space corresponds to a given value of distance or similarity (respectively dissimilarity) between these objects. For example, the more objects are, the closer they lie together. The purpose of MDS lies in visualising the intrinsic structure of data for making it accessible for exploration or analysis. The underlying data may be correlations of objects regarding their characteristics as described by multiple variables.[434]

Applied to product engineering, this method may be used to analyse the characteristic similarities between the parameters of the products in focus. Since this method has been implemented to examine similarities between different vehicles in a competitive environment in this thesis (section 6.1 and 8.3.3.2), the example of vehicles of Porsche AG is used to outline the basic procedure of this technique.

At first, two vehicles of the *same* production series but differing in their vehicle body values shall be examined regarding their similarities. Taking the Carrera und Carrera S as example, they take on similar parameter values for height, width, length, drag coefficient, end face, wheel base and differ regarding performance and fuel consumption. These parameters can be formulated as vectors for the vehicles:

$$\overrightarrow{Carrera} = \begin{pmatrix} height \\ \ldots \\ fuel\ consumption \end{pmatrix} \qquad \overrightarrow{CarreraS} = \begin{pmatrix} height \\ \ldots \\ fuel\ consumption \end{pmatrix}$$

Equation A-1: Vector notation for characteristic vehicle parameters

Subsequently, a scalar distance can be calculated between the two vectors, each of which depicts the eight parameters (eight dimensions):

$$\left| \overrightarrow{Carrera} - \overrightarrow{Carrera\ S} \right| = distance\_1$$

Equation A-2: Scalar distance between the Carrera and Carrera S

The Cayenne turbo as a third vehicle from a *different* production series, which differs in the observed parameters, is equally depicted as a vector. Again, the scalar difference is calculated to the Carrera to determine the difference in distance between the parameters of the two vehicles:

$$\left|\overrightarrow{Carrera} - \overrightarrow{Cayenne\ turbo}\right| = distance\_2$$

Equation A-3: Scalar distance between the Carrera and Cayenne turbo

The resulting distances show that distance_2 is larger than distance_1 due to the characteristic differences between the vehicle concepts. If the distance_3 between the Cayenne turbo and the Carrera S is equally determined, the three vehicles can be arranged in two-dimensional space (Figure A-2):

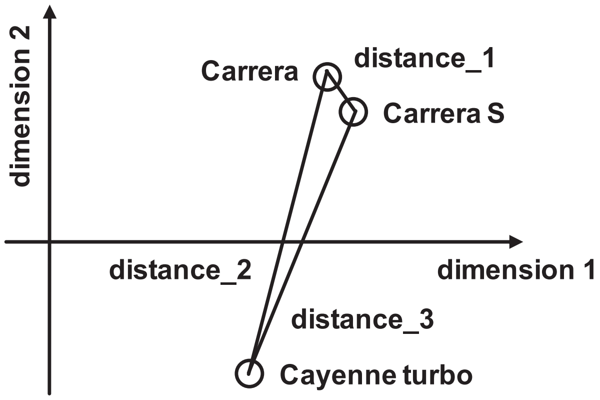


Figure A-2: Collocation of vehicles in two-dimensional space

Using linear regression, the main directions of characteristic parameter combinations, i.e. parameters with strong influence to each other, can be calculated and depicted in the original diagram (Figure A-3):

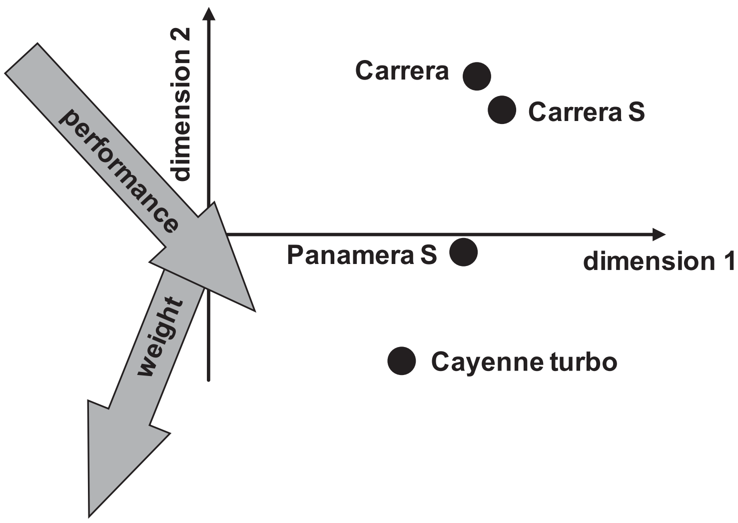


Figure A-3: Identification of directions of parameter combinations[435]

[434] cp. tp Borg et al. 2010, Borg & Groenen 2005

[435] The Panamera S has been added to this visualisation for illustrating another vehicle with characteristically parameters and resulting differences, i.e. arrangement in respect to the others.

To implement this method and to identify these characteristic axes, computational support is necessary. For the purpose of this thesis, algorithms were implemented in Matlab and analysed in a collaborative project between Porsche AG and the IPEK – Institute of Product Engineering. The arrangement of coherent parameters calculated, which served as basis for defining the axes as used in Figure 6-1 and Figure 8-9, can be seen in Figure A-4.

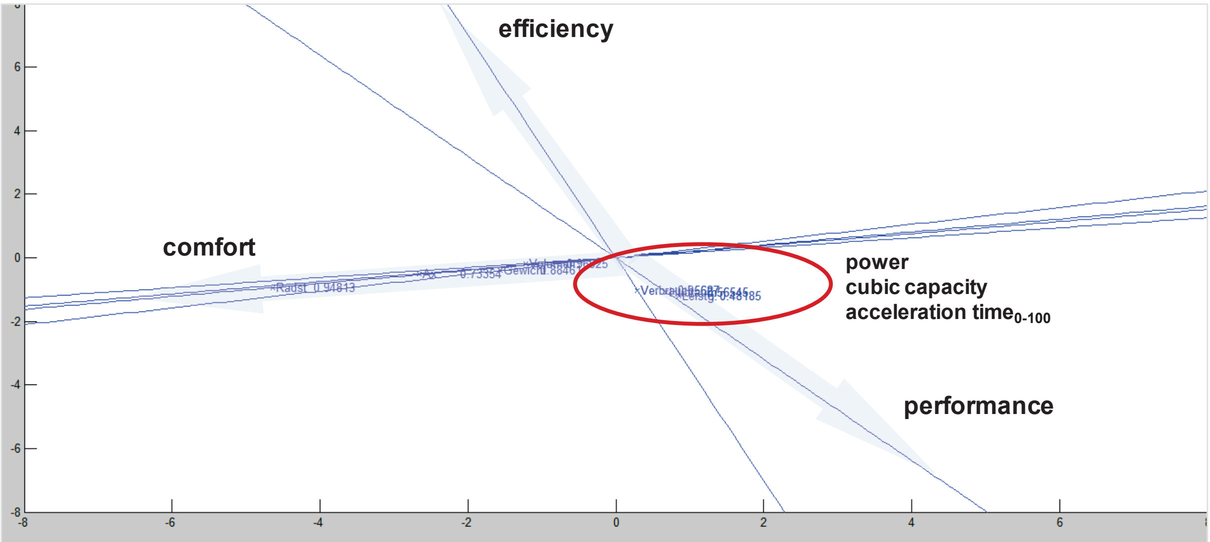


Figure A-4: Computational identification of axes

It should be noted that this arrangement of vehicles in the diagram is not static, but changes in respect to assumed parameters or different characteristics of observed vehicles.

A.1.4 Development of Systems of Objectives

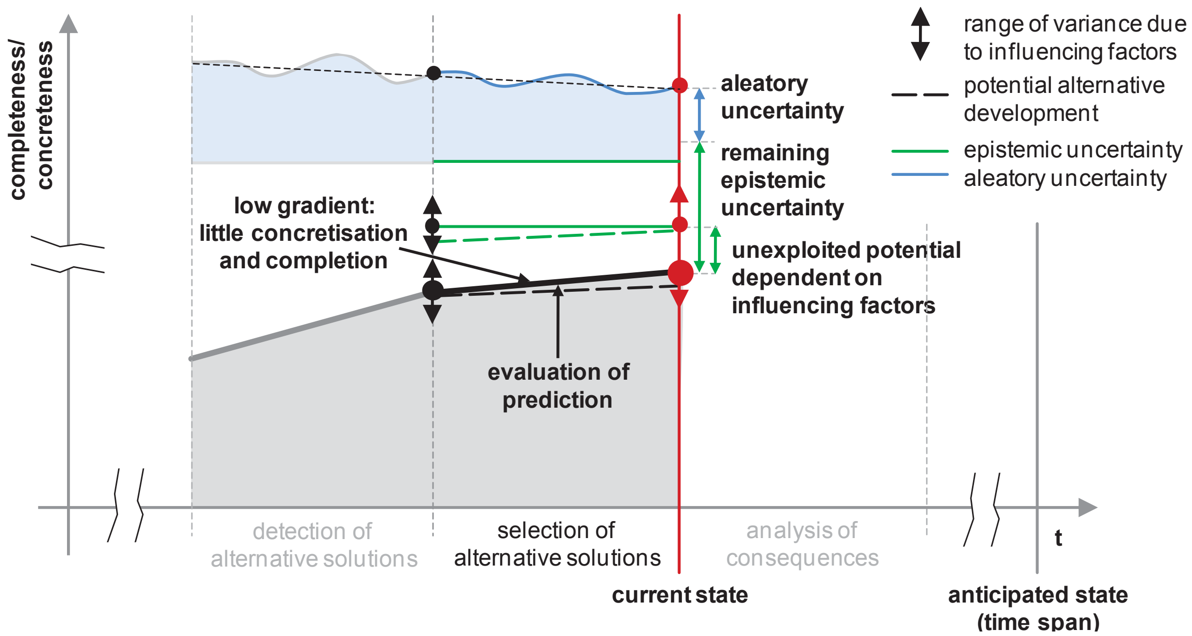


Figure A-5: Development of system of objectives during activity *select solutions*

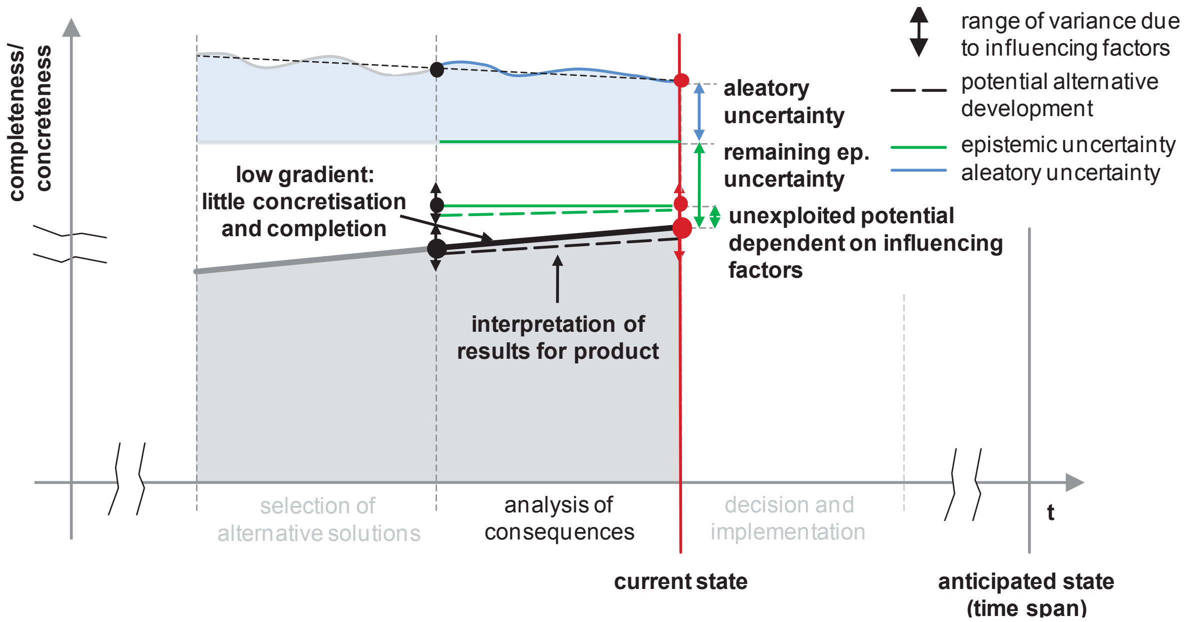


Figure A-6: Development of system of objectives during activity *assessment of significance*

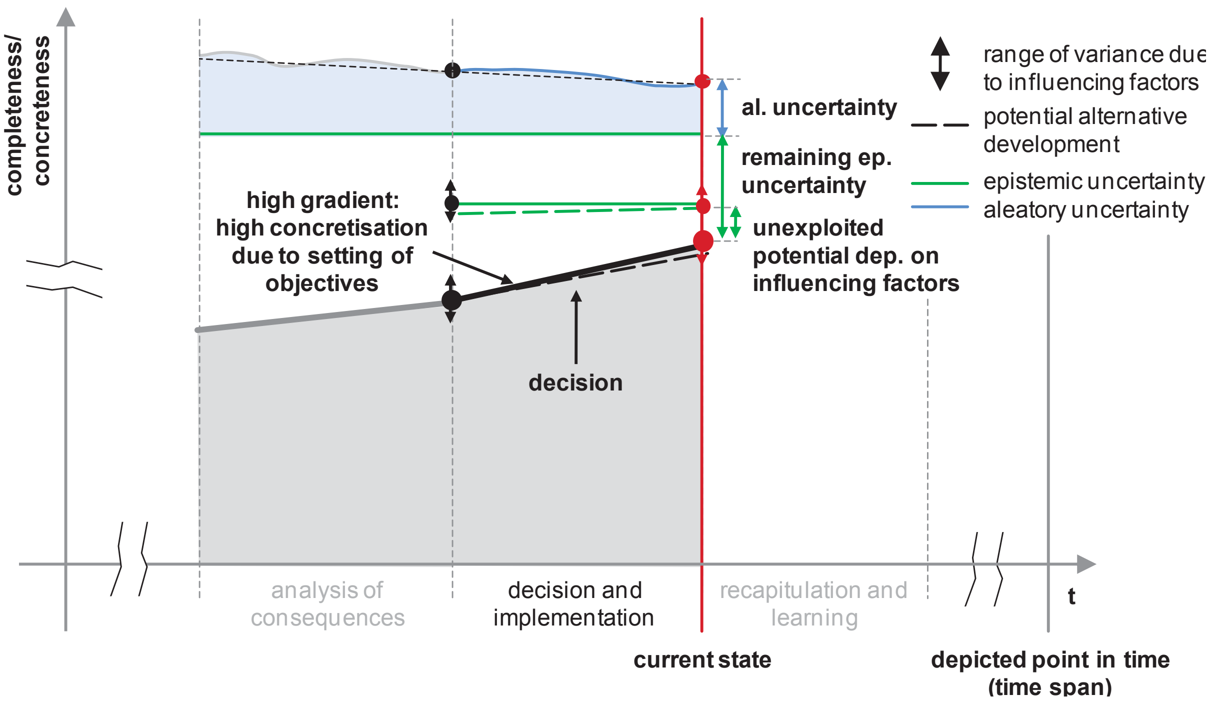


Figure A-7: Development of system of objectives during activity *decision and implementation*

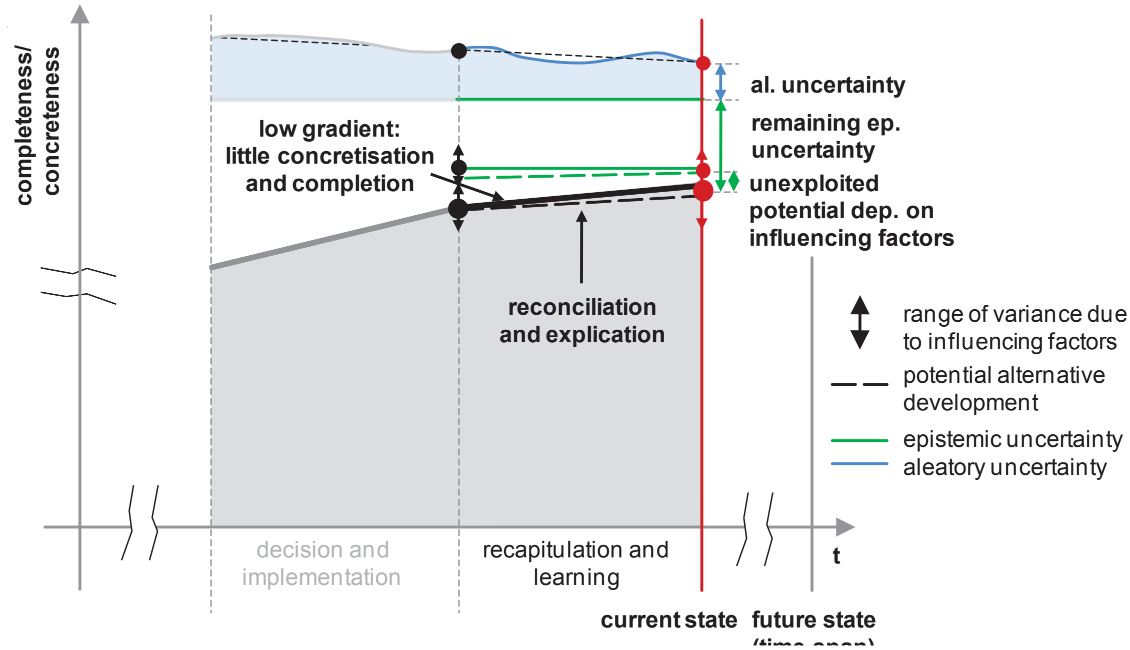
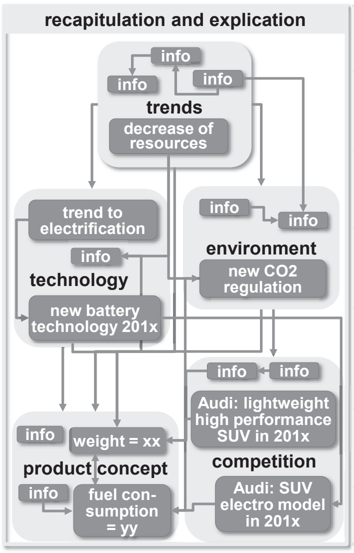


Figure A-8: Development of system of objectives during activity *recapitulation and articulation*



completion ↑↑	concretisation ↑↑	quality ↑↓	consistency ↑↓	comparability ↑↓
• **constraints**	• **constraints**	• **constraints**	• **constraints**	
• **process** content standardisation	• **process** content standardisation	• **process** content standardisation	• **process** content standardisation	• **process** standardisation
• **methods** content standardisation	• **methods** content standardisation	• **methods** content standardisation	• **methods** content standardisation	• **methods** standardisation
• **tools** content standardisation	• **tools** content standardisation	• **methods** content standardisation	• **tools** content standardisation	• **tools** standardisation
• **information** disposability	• **information** disposability reliability measurability	• **information** disposability reliability measurability	• **information** disposability measurability	• **information** disposability
• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge	• **individual** systematics knowledge
• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**	• **aleat./epist. uncertainty**

Figure A-9: Influences on the development during activity *reconciliation and articulation*

A.2 List of Figures

A.3 List of Tables

A.4 List of Equations

A.5 List of Abbreviations and Acronyms

A (AL)	search for alternative solutions (SPALTEN)
cp. to	compare to
e.g.	for example
EU (E)	decision and implementation (SPALTEN)
i.e.	id est, respectively “that is”
iPeM	integrated product engineering model
	(German acronym “integriertes Produktentstehungsmodel“)
IPEK	Institute for Product Engineering
KIT	Karlsruhe Institute of Technology
L (LA)	select solution (SPALTEN)
NL (N)	decision and implementation
P (PE)	problem containment (SPALTEN)
Porsche AG	Dr.-Ing.h.c. F. Porsche AG
S (SA)	situation analysis (SPALTEN)
SPALTEN	problem solving methodology based on ALBERS 2005
T (TA)	analysis of the level of fulfilment

A.6 List of Important Translated Terms

availability	Verfügbarkeit
content-related	inhaltlich
constraint	Randbedingung
endogenous	endogen (z.B. innere Randbedingung)
exogenous	exogen (z.B. äußere Randbedingung)
to articulate	explizieren, artikulieren
formal	formal
measurability	Messbarkeit
operation system	Handlungssystem
quality	Güte (i. Bzg. auf Zielsysteme)
relationship	Beziehung, Relation
reliability	Belastbarkeit
system of objectives	Zielsystem
system of objects	Objektsystem
objective	Ziel

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Curriculum Vitae

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Work Experience

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