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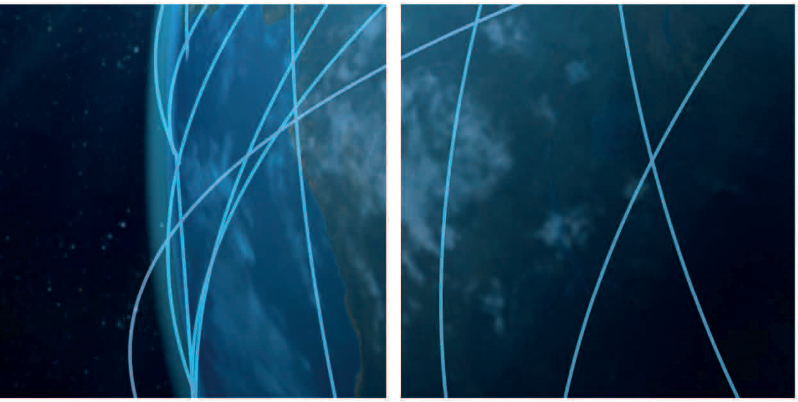
DESIGN STRUCTURE MATRICES (DSM) AND ASSUMPTIONS ABOUT PROPERTIES IN MECHATRONIC SYSTEM MODELS



Advances in Mechatronics

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Preface

The thesis at hand addresses a significant issue in the field of mechatronic system design. Mechatronic System Models (MSM) are a feasible method of supporting and facilitating an interdisciplinary engineering approach. Mechatronic systems are often dominated by one engineering discipline. System models promote equal treatment of all engineering disciplines involved during product development and project execution.

The integration of Design Structure Matrices and assumptions about product properties into MSM provides a major contribution both for academia and industry, especially for the improvement of large and complex development processes. Main outcome of this research study is the enhancement of the MSM approach with the usage of Design Structure Matrices (DSM) as an alternative to System Modelling Language (SysML) along with a strategy regarding the documentation and propagation of assumptions to better identify the ideal iteration return points. The approach has been tested successfully in several design experiments.

It was a great pleasure for me to accompany Dr. Sadlauer on the scientific way to his dissertation and I therefore wish Dr. Sadlauer's work the wide dissemination it deserves in science and practice.

Wels, April 2020

FH-Prof. Priv.-Doz. DI Dr. Peter Hehenberger

Acknowledgement

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Abstract

Several approaches in multidisciplinary product development attempt to better enable the synergetic interconnection between the different disciplines with according models and processes. One of these approaches is the Mechatronic System Model (MSM) approach. This approach uses SysML (System Modelling Language) for a hierarchical representation of the different models and an adaptation of the VDI (Verein Deutscher Ingenieure) 2221 process model. While SysML is accepted in Systems Engineering and due to its relation to UML (Unified Modelling Language) in software development, it is not well established in other mechatronic disciplines, such as mechanical and electrical engineering. The included process model allows for iteration, but lacks an indication of the proper iteration return point to minimize the negative duration effect of the iteration. The present thesis enhances the MSM approach with the usage of Design Structure Matrices (DSM) as an alternative to SysML along with a strategy regarding the documentation and propagation of assumptions to better identify the ideal iteration return points. The reasons for choosing a DSM representation as an alternative are the fact that graphs typically can be easily represented in a matrix form and a significant amount of literature has been published about it. These mentioned adaptations have been applied in a design study of an anti-bruxism device. In addition, the adaptations to the MSM approach have been tested in design experiments with two different design tasks. In the first task, the participants had to properly perform a change in an existing system with visual support of either a DSM or node-link-graphs. The experiment results of this design task showed that neither representation is superior to the other one without prior knowledge of either. In the second design task, the participants had to adjust the thrust of the landing rockets and their ignition times of a moon lander to guarantee a safe landing and to use as little fuel as possible. Half of the participants were advised to record the assumed property values. While the assumption documentation lead to a lower number of iterations, the observations indicated that a higher number of iterations lead to better results when the iteration time is negligible compared to the overall time available. The adaptations to the MSM showed improvements with respect to applicability and quality of the results in the design study and in the experiments. In the design study, adding additional properties to the matrix did not disturb the matrix in the same way an adaptation to a graph would and in the experiment, highly specific information regarding the inconsistency lead to better results. However, not all the intended goals, such as a higher efficiency in iterations and better results when using DSM-representations were fully achieved and further study and practical user experience is required.

Kurzzusammenfassung

Verschiedenste Ansätze in multidisziplinärer Produktentwicklung haben das Ziel der synergetischen Verbindung zwischen den verschiedenen Disziplinen mittels entsprechender Modelle und Prozesse. Einer dieser Ansätze ist jener der Mechatronischen Systemmodelle (MSM). Dieser Ansatz inkludiert SysML (System Modelling Language) für die hierarchische Verbindung der verschiedenen Modelle sowie für eine angepasste Version des Produktentwicklungsprozesses nach VDI (Verein Deutscher Ingenieure) 2221. Während SysML in Systems Engineering und, aufgrund seines Ursprungs aus UML (Unified Modelling Language), in Softwareentwicklung weitgehend akzeptiert ist, mangelt es an Akzeptanz in den anderen mechatronischen Disziplinen, wie im Maschinenbau und in der Elektrotechnik. Der integrierte Produktentwicklungsprozess beinhaltet zwar Iterationen, liefert aber keine Indikation bezüglich geeigneter Rücksprungpunkte, um die Entwicklungszeit möglichst zu minimieren. Die vorliegende Dissertation erweitert den MSM Ansatz um eine alternative Modell-Verbindungs- und Darstellungsmethodik mittels Design Structure Matrizen (DSM) als Alternative zu SysML und liefert eine Strategie zur Identifikation idealer Rücksprungpunkte bei Iterationen über die Dokumentation und Verknüpfung von Annahmen über Parameterwerte. Diese Erweiterungen wurden anhand einer Design Studie eines Anti-Bruxismus Gerätes angewandt. Darüber hinaus wurde die Sinnhaftigkeit dieser Erweiterungen anhand von Design Experimenten erprobt. In der ersten Design Aufgabe im Rahmen der Experimente hatten die Probanden die Aufgabe, Änderungen an einem existierenden System durchzuführen, mit dem Ziel, dass nach den Änderungen keine Inkonsistenzen im System verblieben. Dabei stand entweder eine DSM oder ein Knoten-Kanten Graph zur Darstellung der Abhängigkeiten zur Verfügung. Dieses Experiment zeigte, dass keine der beiden Darstellungen der anderen überlegen ist, sofern die Probanden kein Vorwissen über beide Darstellungen mitbringen. In der zweiten Design Aufgabe im Rahmen der Experimente passten die Probanden den Schub und die Zündzeitpunkte von Landungsraketen einer Mondlandefähre an, um einerseits eine sichere Landung sowie andererseits minimalen Treibstoffverbrauch sicherzustellen. Die Hälfte der Probanden wurde dabei angewiesen, die angenommenen Werte von einer Iteration zur nächsten zu dokumentieren und den Erfolg der Iterationen zu evaluieren. Dieses Experiment zeigte zwar, dass die Dokumentation die Anzahl an Iterationen verringert, allerdings wurde mit einer höheren Anzahl an Iterationen eine höhere Erfolgsrate erzielt. Dies scheint stärker der Fall zu sein, wenn der Zeitaufwand für die Iterationen gegenüber der Gesamtzeit verschwindend gering ist. Die Erweiterungen des MSM Ansatzes zeigten Verbesserungen in der Anwendbarkeit und der Ergebnisqualität in der Design Studie wie auch bei den Experimenten, allerdings konnten die Forschungshypothesen nicht nachhaltig bestätigt werden. Zur vollständigen Bestätigung der Erweiterungen sind weitere Forschung und praktische Anwendung erforderlich.

Contents

Acronyms

ABH Anti-Bruxism-Hat

AF Architecture Framework

ANOVA Analysis of Variance

ARC Areas of Relevance and Contribution

CAM Cambridge Advanced Modeller

CASE Computer Aided Software Engineering

CPM Change Prediction Method

CR Common Repository

DRM Design Research Methodology

DSM Design Structure Matrix

ECTS European Credit Transfer System

EKB Engineering Knowledge Base

FFE Fuzzy Front End

FMEA Failure Mode Effect Analysis

GPML General Purpose Modelling Language

GUI Graphical User Interface

ID Identifier

IVM	Impact Velocity Measure
IMDP	Institute of Mechatronic Design and Production
MBDL	Model-Based Description Languages
MBSE	Model-Based Systems Engineering
MDM	Multiple Domain Matrix
MSM	Mechatronic System Model
NPV	New Product Development
PLC	Product Lifecycle
PLM	Product Lifecycle Management
SysML	System Modelling Language
TRL	Technology Readiness Level
UML	Unified Modelling Language
VDI	Verein Deutscher Ingenieure
VHDL	VHSIC (Very High Speed Integrated Circuit) Hardware Description Language-Analog and Mixed Signals
XML	Extensible Markup Language

1. Introduction

Many products rely on several engineering disciplines to be able to fulfil the tasks they are intended for. During the development of such products, these disciplines have to be considered and involved. The resulting interdisciplinary (between different disciplines) interactions cause several issues for the product, the development process and the ensuing production of the product.

In the context of this work, the author specifically distinguishes between the terms discipline and domain. Discipline is used in reference to technical disciplines, such as mechanical engineering, information technologies and electronics, whereas domain is used for application domains which can occur within and across disciplines, such as plant engineering, intralogistics and robotics.

As shown by the numerous successful products, companies are able to handle these issues well. Nevertheless, there is a noticeable pattern that product development could be done more effectively and efficiently. This notion is mostly promoted by companies that thrive on innovation and academia (often in cooperation with such companies) who suggest ways and tools to better develop better products.

Academia provides several possible approaches for successful multidisciplinary (incorporating different disciplines) product development. These approaches have been extensively tested in laboratory environments and in industrial case studies. Over the last decades, many of these approaches were taught to generations of new engineers. This might suggest that over the years, these methodologies have reached industry and are successfully implemented. For some of them, such as the V-Model for mechatronic system development [VDI03], this is true to some extent. However, even for the rather successful implementation of the V-Model, only specific parts, such as the triangular connection of system design, system integration and the assurance of properties are actually applied as guidelines at the management level. Even in projects officially following set procedures for product development, in details the realizations contain major exceptions and deviations from these procedures.

As pointed out by Klein [Kle09], there are several reasons why procedures are not being followed. Procedures are difficult to adapt, however, suitable adaptation is a necessity in the highly dynamic product development landscape. Therefore procedures are often ignored instead of being re-evaluated. In addition, the highly dynamic nature of product development in combination with the interconnections with several disciplines creates a complex environment. As stated by Klein "*In complex settings, in which we have to take the context into account we can't codify all the work in a set of procedures.*" [Kle09, p. 19]. This further complicates the standardization of product development processes.

Another cause is a certain lethargy of companies with respect to changing their processes. To quote Klaus Zeman, "*As long as the established processes work and the suffering of the companies is not big enough, no new processes will be implemented.*" The author would even go as far as calling this Newton's first law of change in companies: When viewed in an inertial reference frame, a company that is at rest, remains at rest, unless acted upon by an external force. This force could be in the form of market pressure either from competitors or the customers. The most convenient approach for companies is being a fast follower, i.e. installing practices as soon as others have shown to be successful with them.

The pressure of the market to provide better products is pushing the technological limits. A key aspect of extending the capabilities beyond the existing limits is the previously already addressed integration of different disciplines. A key area for the integration is the product architecture, as it defines the interrelations between the components, which most of the time still have to reflect a set of specific disciplines. The creation, integration and communication of the product architecture therefore is a cornerstone of multidisciplinarity.

The Mechatronic System Model (MSM) approach [Fol12, FHP+11, FHZ12a, FHZ12b] is one example for such a multidisciplinary product development framework. The MSM approach tackles the interconnections of different disciplines. It provides a procedure for development that is flexible enough to address the highly dynamic changes. At the same time, it provides a clear structure as a guideline not to lose track of the overall progress. Even though case studies show its successful implementation, for various reasons it is far from being standard practice in any companies. First, it currently is a set of guidelines that is not supported by tools which can be readily industrially applied. Second, some aspects require improvement, such as the handling in a concurrent environment along with the practical realization of the process. Third, the currently applied General Purpose Modelling Language (GPML) SysML as the language of choice for system model representation has acceptance issues in industry. One goal of this thesis is to overcome these issues and get the MSM approach closer to industrial readiness for it to be applied productively in companies.

A major component of the MSM approach is the procedure model for product development. This procedure model is an extension of the VDI 2221 [VDI93] and strongly resembles a stage-gate process [Coo11]. A significant difference of the procedure model of the MSM approach in comparison to other product development procedures is the acceptance and inclusion of iterations as an essential part of product development. However, even though iterations are included, in a majority of cases it remains unclear, where the iteration has to return to. The discussion of the iteration return point and specifically the handling of assumptions about product properties as a reason for iterations mark another goal for this thesis.

In the context of this thesis, the mentioned aspects regarding industrial readiness of the MSM approach and the handling of iteration return points are discussed and possible solutions are presented. First, an alternative representation for interconnections of dependencies is presented in the form of matrix representations (Design Structure Matrix (DSM) and Multiple Domain Matrix (MDM)). Second, the handling of assumptions as placeholders for missing information and its role as a cause for iterations are discussed.

The research questions in this thesis are:

- How can matrix based representations be applied within the MSM approach to extend its usage and acceptance beyond systems engineering to achieve better product development results?

- How can assumptions as potential reasons for iterations be tracked and be utilized for the identification of appropriate iteration return points to limit wasteful iterations?

The answers suggested in this thesis are matrix based representations for the extension of the MSM approach beyond systems engineering and assumption documentation with an ensuing ranking system for the identification of iteration return points. The ensuing hypotheses are listed in the following.

- The extension of the MSM approach with matrix based representations as an alternative to SysML will improve the acceptance of the MSM approach and provide better product development results.

- The proper documentation and propagation of assumptions, including their history will decrease the use of resources by decreasing unnecessary iterations while still achieving equivalent or better quality of results.

1.1. Structure of the Thesis

The research for this thesis was performed based on the "*DRM: A Design Research Methodology*" structure suggested by Blessing and Chakrabarti [BC09]. In addition to the recommended structure, the thesis implements some methods suggested in the DRM, such as the reference and impact model and the diagram regarding the Areas of Relevance and Contribution (ARC) [BC09].

The contents of the chapters of this thesis reflect the DRM. The introduction provides a short glimpse at the problem and the motivation for this thesis along with the structure. The related work presented in Chapter 2 incorporates the major part of the Research Clarification and gives an insight into the work that has already been done in the areas considered for this thesis. The rest of the Research Clarification, based upon the related work and on the personal experience of the author, concerns observing the environment in which the present research is intended to have an impact on. After the initial Research Clarification, the thesis contains a Descriptive Study I presented in Chapter 3, summarizing the observations of the state of the art in two reference models. This was followed by a Prescriptive Study, indicating how the state of the art can be improved.

Chapter 4 discusses the basic concept and provides a case study of the practical implementation. The basic concept chapter shows the idea behind the solution environment and the enhancements and adaptations made to the basic concept of the MSM approach. The intended goal is presented with the impact models. The case study shows the implementation of the MSM approach with the indicated extensions, including software realization in combination with existing software products. Some of the assumptions and success criteria were evaluated in the Descriptive Study II which comprises design experiments with two design tasks. These design experiments had the goal to support the design hypotheses and are presented in Chapter 5. Following the results of the design experiments, some further adaptations to the MSM approach seemed necessary. These are discussed and presented in Chapter 6. The conclusion and outlook in Chapter 7 provides a summary of the findings along with future potential research.

This thesis uses several examples to explain how the approaches presented and discussed are intended to work or to exemplify their application. In addition to the examples, a questionnaire, a case study and two design experiments were used for identification and evaluation of the research questions and hypotheses established in this thesis. Figure 1.1 presents an overview of specific content covered in this dissertation for the different stages of the DRM methodology and the respective study methods

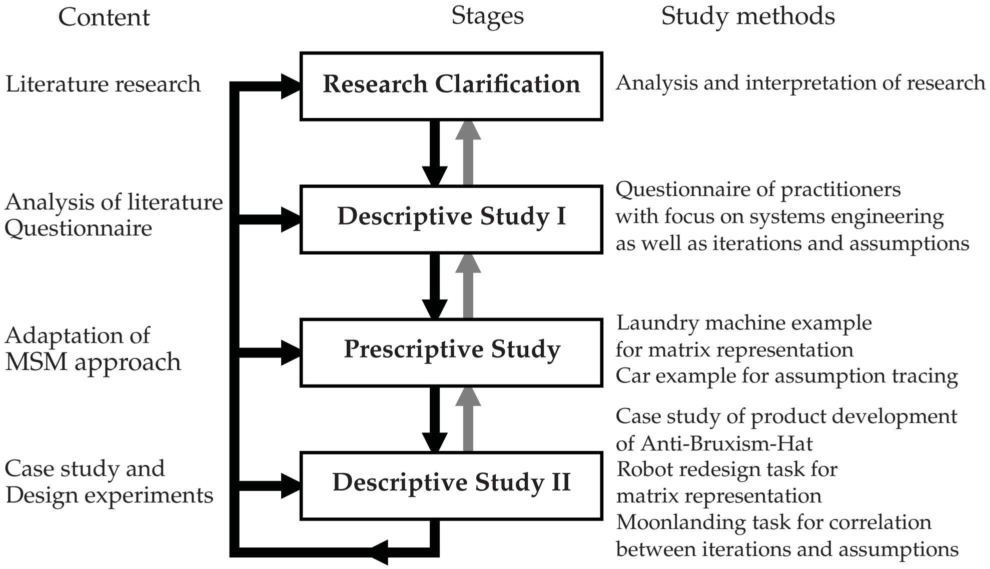

Figure 1.1.: Contents and study methods for DRM stages (adapted from [BC09])

implemented. Table 1.1 provides a more detailed overview of the study methods. The difference between the design tasks and the case study is in the extent and the focus. The design tasks are used to highlight certain specifics, whereas the case study shows the application of the whole MSM approach. In addition to the design tasks mentioned in Table 1.1, several small examples, such as navigating through a maze or the development of a crankshaft of a diesel engine are used to explain certain aspects of product development.

1.2. Thesis Summary

The introduction is followed by the related work chapter (Chapter 2). Within this chapter, approaches for multidisciplinary product development are discussed. These include matrix based representations, such as the Design Structure Matrix (DSM) and the Multiple Domain Matrix (MDM). In addition, the role and significance of iterations within the design process are discussed. The 3rd Chapter addresses the findings through collaborations with industry and the questionnaire of the practitioners. The insights gained and discussed in Chapter 3 present additional opportunities for improvement of the MSM approach. The 4th Chapter addresses the main adaptations to

Table 1.1.: Overview of study methods and outcomes

Study method	Name	Description
Questionnaire	Questionnaire	The questionnaire among the participants of a systems engineering course is used to identify and strengthen research arguments.
Example	Laundry machine	The laundry machine example was used as a main case study for the MSM approach by Follmer et al. [FHP$^+$11, FHZ12a, FHZ12b]. Thus, it is used as the main reference for the validation of the matrix-based representation.
Example	Car concept	The car concept is used to provide an example for assumptions about product properties in product development and to show their interrelations.
Case study	Anti-Bruxism-Hat	The Anti-Bruxism-Hat is used to demonstrate the application of the enhancements to the MSM approach.
Design task	Robot redesign	The robot redesign task is used for the design experiment with the goal to validate the better suitability of the matrix-based-representation for the MSM approach in comparison to node-link graphs
Design task	Moon landing	The moon landing task is used for the design experiment with the goal to validate the interconnections between the documentation of assumed property values and iterations.

the MSM approach in light of these findings and presents a case study of the matrix representation of interconnections within the MSM approach and the documentation of assumptions regarding properties. The 5$^{\text{th}}$ Chapter discusses the design experiments intended for the validation of the research hypotheses. The 6$^{\text{th}}$ Chapter presents further adaptations to the MSM approach resulting from the design experiments and provides an outlook for further research activities based on this thesis. Chapter 7 concludes the thesis with a summary of the findings and an outlook for the future.

2. Multidisciplinarity and uncertainty in product development

Product development faces numerous obstacles. As mentioned in the introduction, products most of the time require several disciplines to successfully interact. This interaction and combination of disciplines creates additional obstacles. Torry-Smith et al. [TSQA$^+$13] address several of these obstacles which they attribute to mechatronics. Similarly, Alvarez Cabrera et al. [AFT$^+$10] identify obstacles, especially from a control engineering perspective, attributed to mechatronic systems. Some of these obstacles, however, are not rooted in multidisciplinarity, but are general problems, such as the difficulty of exchange or transfer of design models and information or data. Both of the aforementioned publications list this obstacle, which at its root is a communication problem, aggravated by multidisciplinarity (obstacle F in [TSQA$^+$13, p. 011005-4]; first obstacle in [AFT$^+$10, p. 877]). Nevertheless, other obstacles mentioned are clearly due to the consideration of different disciplines, such as comparison or consideration of designs of different disciplines (obstacle B in [TSQA$^+$13, p. 011005-4]; 4th obstacle in [AFT$^+$10, p. 877]). This comparison is difficult, as the different disciplines do not have a common base which would allow for simultaneous comparison or consideration.

The diversity of design is also exemplified by Chakrabarti and Blessing [CB14], who provide a large collection of different viewpoints regarding theories and models of design. Aspects of some of these theories contradict each other. Nevertheless, all have their validity regarding certain areas and are able to address some of the obstacles in design.

Literature suggests various solutions to mitigate these obstacles through various measures. Some suggested solution environments include processes recommended for product development. Others provide specific methods and along with them appropriate tools to overcome specific obstacles, such as communication barriers between disciplines. In the following sections the author discusses related work addressing the interconnections between and combination of the disciplines, as well as iterations in the context of product development.

2.1. Multidisciplinarity

When discussing the topic of multidisciplinarity it is necessary to discuss systems engineering as one approach intended to address several disciplines. The definitions of systems engineering are manifold with a good example provided in the following.

Systems engineering is a multidisciplinary approach to develop balanced system solutions in response to diverse stakeholder needs. Systems engineering includes the application of both management and technical processes to achieve this balance and mitigate risks that can impact the success of the project. The management process is applied to ensure that development cost, schedule, and technical performance objectives are met. [FMS11, p. 4]

An approach within systems engineering to use models as sources for creation and vessels for communication for prediction and evaluation within a project is provided by Model-Based Systems Engineering (MBSE). One goal of MBSE is to establish a different paradigm by using models as sources and vessels for the creation and communication of properties and can replace the traditional document-based systems engineering approach [FMS11].

MBSE applies systems modeling as part of the systems engineering process [..] to support analysis, specification, design and verification of the system being developed. A primary artifact of MBSE is a coherent model of the system being developed. This approach enhances communications, specification and design precision, design integration and reuse of system specification and design artifacts. [FMS11, p. 15]

The General Purpose Modeling Languages (GPML), such as UML (Unified Modeling Language) and SysML (Systems Modeling Language), and Model-Based Description Languages (MBDL), such as Modelica and VHDL-AMS (VHSIC (Very High Speed Integrated Circuit) Hardware Description Language-Analog and Mixed Signals) represent ways to realize MBSE. Some of these languages, such as SysML, are spawned by MBSE whereas others, such as VHDL-AMS, have developed rather independently from MBSE, still attempting to achieve the same goals as MBSE. This further confirms the goals of MBSE. The GPML are sometimes also referred to as graphical modeling languages. These terms in this thesis are used interchangeably, with GPML as the preferred option, but graphical modeling languages used when the source uses this term.

Understandably, systems engineering and product development have many commonalities. While it is overlapping with systems engineering in certain areas, such as the representation of systems, product development has a wider reach, as it also concerns

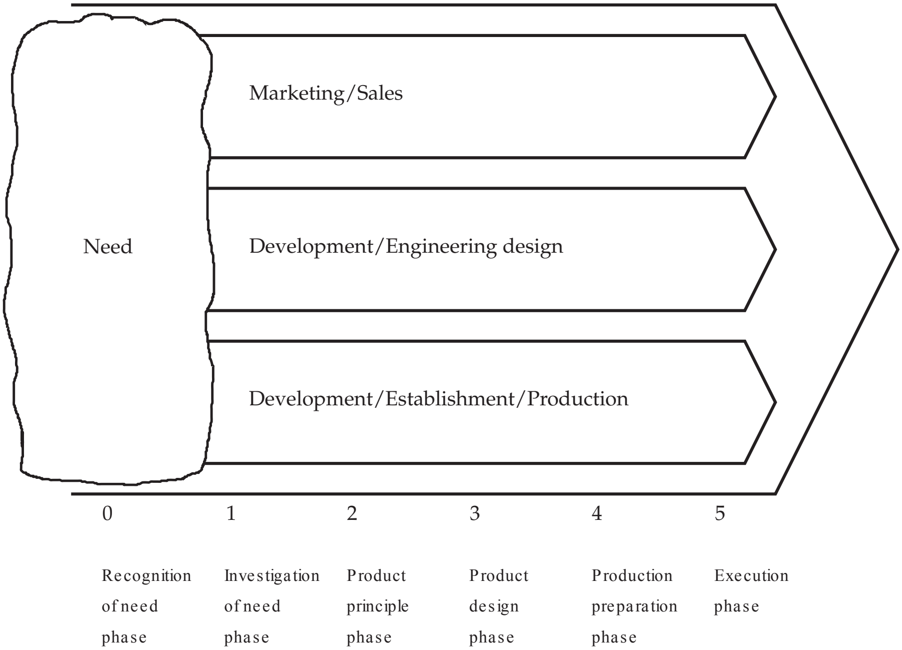

Figure 2.1.: Areas and design phases of Integrated Product Development according to [AH00]

additional product (system) related aspects, such as marketing, production or distribution. These are not inherently part of systems engineering. Nevertheless, the similarities are so strong that the terms in some contexts are used interchangeably.

Various approaches and publications address the situation of product development. Andreasen and Hein [AH00] refer to their strategy as the *integrated product development*. For them, an identified need is the origin of a product to be developed. They suggest three main areas that have to be combined for successful product development. These are marketing/sales, development/design and development/establishment/production. These areas are represented in three different strands, which are then segmented into the design phases recognition of need, investigation of need, product principle, product design, production preparation and execution (see Figure 2.1).

Andreasen and Hein emphasize the interactive nature of product development [AH00, p. 23] and highlight that it has to be included in a larger management cycle. In addition, they identify different roles that are of significance during product development, such as the executive (the board of directors, proprietor, etc.), the project leader, the team member and emphasize on specific problems the different roles have to address. Further, they also mention the role of "nobody", highlighting general shortcomings, e.g. due to a lack of set responsibilities. Andreasen and Hein focus on the process of product development and some of the included roles, but do not discuss the specific methods and tools or information management.

Ehrlenspiel and Meerkamm [EM13] discuss integrated product development from a mechanical engineering perspective. They refer to the VDI 2221 [VDI93] as a framework for the different phases of the product life cycle and present methods for the individual tasks to be performed within the respective life cycle phases. In addition to the traditional mechanical engineering view, they put the human in the center of technical problem solving and address aspects relevant for an industrial application of product development, such as organization and the inclusion of cost considerations. Their observations are supported by various examples.

During the discussion of the human as the central part of product development, Ehrlenspiel and Meerkamm [EM13] also suggest different levels of processes, ranging from the overall process for product development, to individual tasks down to the trial and error behavior of individuals. They also discuss the significance of the definition of means and the goals regarding the problem. Problems where the means are defined and available, and where the goal is clearly stated are straight-forward tasks. When the means are not available or not defined it can be referred to as a means problem. When the goal is not defined it can be referred to as a goal problem. When neither the goal nor the means are clear, it is a goal and means problem. Rittel and Webber call problems without goals being defined wicked problems [RW84, RW73].

These product development approaches, all referred to as integrated product development have several commonalities. Vajna [Vaj14] compares them and provides the Magdeburg Model of integrated product development as a further evolution of the previously presented approaches. The Madgeburg Model considers market, product and production in parallel and is based on process cycles and specifications. At the same time this model incorporates the interaction of humans, organization, methods and technologies under regard of the dynamics (also addressing its causes) of development processes. The significant enhancements of this approach in comparison to other integrated product development approaches are the humans in the center of the whole product life cycle, the cooperation of development goals of appealing design while fulfilling the functions and using a network as a dynamic organizational form for increasingly parallel activities [Vaj14, p. 39ff].

Over time, integrated product development approaches, as well as systems engineering, incorporated a stronger focus on the human. These considerations concern all the stakeholders, which of course include the customers and suppliers, but also the designers. The significance of the designers in the design process is highlighted by Cross