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ON THE INTERACTION BETWEEN THE ENGINEERING DESIGN AND THE DEVELOPMENT PROCESS MODELS — PART I: ELABORATIONS ON THE GENERALLY ACCEPTED PROCESS MODELS

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Models of the engineering design process and of the development process nowadays present similar forms in the engineering design literature and interact in a similar way. These models are often presented as generic, in order to be used in a wide area of applications. This interaction is, however, not unproblematic, and in this publication we present some important issues and challenge the generic aspect of these models. In order to increase clarity we have divided the publication into two parts. In Part I, the generally accepted engineering design and development process models are presented. The fundaments of the development model and the motivations behind its current form are highlighted. In Part II, the consequences in the form of severe shortcomings resulting from the interaction of the engineering design and development process models are highlighted. These shortcomings do not disappear when the systematic design process model is applied with alternative development process models. The implications for the further development of methodologies supporting the design and development models are discussed.

Keywords: Engineering design process model, Development process model.

1. INTRODUCTION

Many would take the view that the different engineering design process models presented in the literature now have converged and present a common backbone with only cosmetic variations. Correspondingly, the different development process models in the literature in which the engineering design process is embedded present large similarities. (Note that the term *development process* in this text regroups both the *product planning* and the *product development process*.)

The engineering design process was originally conceived as a stand-alone process, in a time where over-the-wall development was common and the focus was on the creation of the product technology as such. The goals to be achieved by introducing engineering design process models were primarily to improve the efficiency and effectiveness of the engineering designer's activities.

The growing competition on the market, domestically and internationally, called for a broader perspective on the development of the product-to-be then represented within engineering design. In this

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perspective, important aspects were to prioritize market needs and establish a well-defined development strategy — to mention but two of the activities required during the development process. In other words, from being an activity performed more or less single-handed by the engineering designer, the development of a product became a highly complex endeavour involving a number of competences representing different functions in the company.

As a consequence of this progression from “pure” engineering design to product development, the engineering design process models became integrated in the development process models, where strategic, planning and marketing perspectives were suggested. On the whole this integration was accomplished in principally two ways, either by “extending” the engineering design process model into a development process model (e.g. [1]) or by utilizing the engineering design process to, in greater detail, structure the development process models emanating from studies of development processes in practice, where marketing and managerial aspects represented the dominating foundation upon which the process models were established (e.g. [2]).

The integration efforts based on these terms introduce several important shortcomings. The overall objective set out for this publication is to elaborate on these shortcomings. For reasons of clarity we have decided to present the work in two papers — Part I and Part II.

Part I begins with a review of the constitutive elements of the generally accepted engineering design process model (that is, the systematic engineering design process model), followed by a discussion of the integration of the engineering design process into the development process. The fundaments of the development model and the motivations behind its current form are also highlighted.

In Part II [3] the shortcomings resulting from the interaction between engineering design and development process models are presented and discussed in some detail. The generic aspects of the commonly accepted structure of the current development model are questioned, and alternative development strategies are presented. The consequences for further development of engineering design process and the development process models are discussed.

2. THE GENERALLY ACCEPTED ENGINEERING DESIGN PROCESS MODEL

From 1972 to 1974, Pahl and Beitz, together with colleagues, performed an extensive synthesis of the engineering design body of knowledge, primarily developed in Germany. This synthesis was originally published in the German journal *Konstruktion* as a series of articles “Für die Konstruktionspraxis” [4] and further edited in the book *Konstruktionslehre* [5]. In parallel, the VDI 2222 “Design Methodology — Conceptualizing Technical Products” [6, 7] was developed. After *Konstruktionslehre* was translated into English under the supervision of Wallace with the title *Engineering Design* [8], the German systematic design approach could be spread into the English-speaking engineering design community. This dissemination was also enhanced by the exchange between the German researchers and MIT during the 80s, and the ICED’87 conference in Boston. Ullman’s *The Mechanical Design Process* [9] has been derived from “*Konstruktionslehre”* [10, p. 6], and so is the design process part of Ulrich and Eppinger’s *Product Design and Development* [11]. Finally, Hubka and Eder, in their *Design Science* [12, 13], another synthesis work on engineering design, evoked different possible approaches for an engineering design process model and recommended a model with similar premises as those utilized by Pahl and Beitz and in VDI 2222 [13, p. 133]. There is also an agreed conception of the constitutive elements of the engineering design process. These aspects are summarized below [14, p. 200].

The systematic engineering design process model aims at making it easier to find an optimal design for the product-to-be. To that end it is necessary to encompass the broadest range of solutions, that is, to search for solutions in a structured, systematic way. The breadth-first top-down strategy is adopted, which means first finding the largest possible number of abstract solutions (breadth-first) and then more concrete ones (top-down). The different concretization levels are based on the product models utilized, whose archetype is found in Hubka’s technical system (TS) model [15, 16]. The reasons are that each solution on an abstract level represents a set of different concrete solutions, and that it is more costly and time-consuming to develop, describe and evaluate concrete solutions than abstract ones. This model aims at being generic, that is, independent from industrial branches [17] and technical domains [1, p. 10].

The phases into which the systematic engineering design process models are divided vary slightly among the authors, but the steps along these phases are highly similar. In Pahl and Beitz [1][a] and Hubka and Eder [13], the phases are: conceptual design, embodiment design and detail design. These are preceded by a planning phase. In Ulrich and Eppinger [2], the engineering design process consists in conceptual development, system-level design and detail design. Depending on how the term *design* is understood, some authors include the task clarification, i.e. mainly the definition of the specifications, in the planning phase [1; 17, pp. 78; 18, p. 4; 19, pp. 3940; 20, p. 9; 21, Chapter 2; 22, p. 61], others as a design step [2; 23, pp. 13; 24, p. 23; 25]. As everybody agrees on this activity as being important for the engineering design activity and, importantly, as this was proposed in some of the early works [26; 27] as a motivation for a systematic engineering design, we will include it as a design step in the conceptual design phase.

The conceptual phase consists first in the establishment of the design specifications (the requirements). The development of the concept, or principle solution, is achieved through the establishment of function structures, the search of sub-concepts based on (hopefully) different working principles for each function and the combination of the working principles into concept variants that are subsequently evaluated. The embodiment phase consists in the development of structure variants of the chosen concept (product architecture, layout), form giving, and dimensioning and selection of material first for the main functions and then for the auxiliary functions. This phase includes the use of Design-for-X elements. Finally, the detail design phase comprises the detailed drawing of the technical system and its components, and checking for standards and "the detailed optimisation of shapes, materials, surfaces, tolerances and fits" [1, p. 437].

The complete engineering design process is presented Figure 1. This model illustrates, in other words, the contents of the generally accepted engineering design process.

3. INTEGRATION INTO THE DEVELOPMENT PROCESS

Originally, the literature on the engineering design process focused on the development of procedures, methods, and heuristics for assisting the designer in his/her creative activity, helping him/her avoid design errors and improving performance. Up to the 70s, much of the development is of an over-the-wall kind: the assignment is given from the outside; the engineering designer is supposed to work alone, in front of his/her drawing board [28, Foreword]. The engineering designer receives a design task, develops his/her contribution in the form of a detail, component or subsystem and hands it over to the design team (complex products) or to other departments of the company. With the rise of competition, the design activity is increasingly concerned with the planning of product development. Product planning was not present in the "Für die Konstruktionspraxis" series — see especially articles [29] and [30], which describe the engineering design process model and the task clarification step respectively — but is a part of the draft of VDI 2221 (1973) [6], and in 1976–77 the product planning phase and its links to the engineering design phases are introduced in the books by Koller [20] and Pahl and Beitz [5]. It appears also in other countries: for example the Swedish Society of Mechanical Engineers ("Sveriges Mekanförbund") published a report on product planning in 1974 [31]. The product planning phase and the engineering design phases, conceptual design and embodiment design, are now the objects of separate VDI guidelines — VDI 2220 [32] for product planning, VDI 2222 [33] for conceptual design and VDI 2223 [34] for embodiment design. The engineering design process and the development process are so integrated in the literature that they are often used together. Koller [20, p. 6] and Pugh [25, p. 5] assimilate their design process to the product development process; the guideline VDI 2221 *Systematic Approach to the Design of Technical Systems and Products* [17] is now denoted *Systematic Approach to the Development and Design of*

[a] Unless otherwise specified, the works that have been edited several times are referred to by the last English edition.

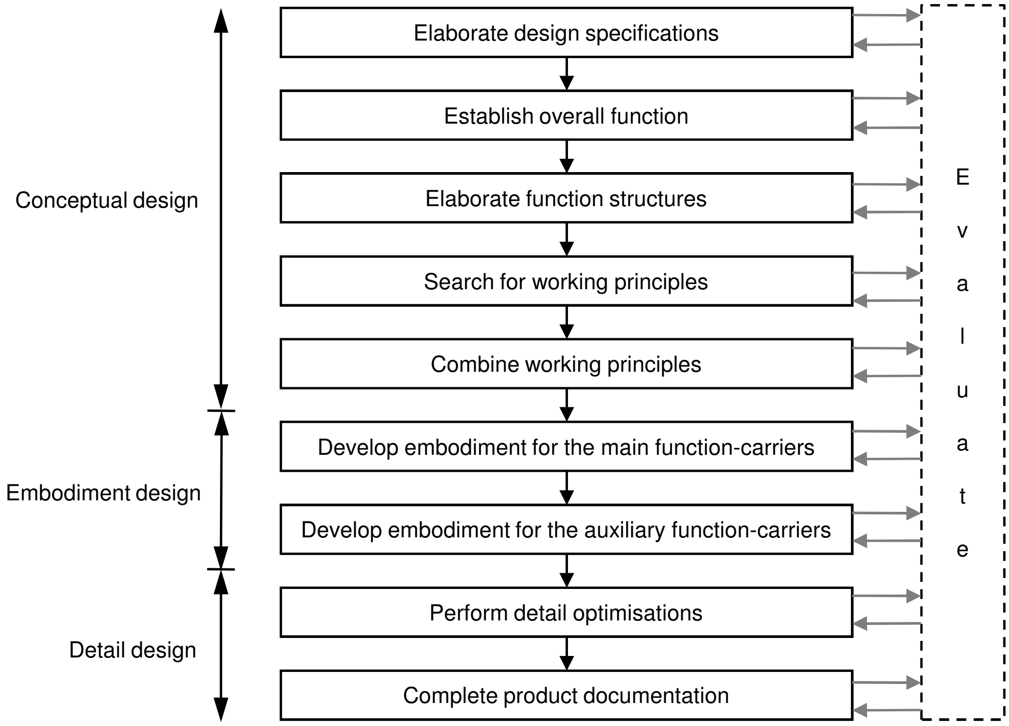

Figure 1. The systematic engineering design process model — the generally accepted process.

Technical Systems and Products [35]; P&B's chapter "Process of planning and designing" [36] is now renamed "Product development process" [1]; Ulrich and Eppinger's book is named *Product Design and Development* [2]; Ullman [22, p. 61]'s mechanical design process includes product planning and product development. This is not a sign of confusion; the general distinction between design and product development is made clear in VDI 2221 for example [17; 35]: Product development is the "[p]urposeful application of the results of research and experience, for example of a technical or economic nature" [17, p. 31; 35, pp. 39–40]; the engineering design process is the "[t]otality of the activities with which all the information necessary for producing and operating a technical system or product is processed in accordance with the task. The result is a set of product documents" [17, p. 30; 35, p. 40]. This indicates, however, that the generic systematic engineering design process model above is used as is to determine the phases of the development process models for technical products in the engineering design literature. This interrelation between design and development is so generally accepted today that the ISO 9000:2000 standard states that '[t]he terms 'design' and 'development' are sometimes used synonymously and sometimes used to define different stages of the overall design and development process' [37, Note 1 of Definition 3.4.4].

Although once again there are some variations in the models, the way the design process is integrated as a part of the development process is similar among authors. The reader might compare Olsson [38], Pahl and Beitz [1], Roozenberg & Eekels [21, pp. 11ff], Sveriges Mekanförbund [39], Ullman [22], Ulrich and Eppinger [2], VDI 2222 [7; 33], Pugh [25]. The development process consists in 1) a product planning — also called *pre-project planning* [40] or *fuzzy front end* [41] — phase and 2) the actual product development phases. This model corresponds also to the *development funnel* presented by Wheelwright and Clark [40]. In the product planning phase, the current situation of the company, market and environment is analysed to guide product idea search and evaluation and detect opportunities. This analysis includes the gathering of information concerning the company development strategy (or product policy), capabilities and core competences, the market situation and evolution, the technological evolution, and other environmental data. Following the analysis, a set of relevant criteria is defined; product ideas are searched for and screened using these criteria. A product portfolio is then determined, and the different selected projects are sequenced in time according to determined priorities. Each individual project is then started and follows the engineering design process presented above.

Beyond the objective of developing products of optimal performances, this funnel development model takes into account further aspects. Wheelwright and Clark [40, pp. 14, 33] have observed that an individual product development project must avoid addressing strategic and fundamental organizational issues; because this results in delays as the senior management is often no longer involved, it takes a long time to achieve consensus and resolve conflicts. These aspects must be addressed during the pre-project phases. The funnel development also allows easier co-ordination and planning [2, p. 12].

Another aspect is that virtually all companies must comply with the ISO 9004:2000 and ISO 9001:2000 standards [37; 42]. These standards require that the requirements be determined prior to the start of a development project and that the development phases and validation be explicitly described. The funnel development model is compliant with the quality management systems standards.

Finally, the aim is to maximise the number of product development successes. The products chosen for development are those that present the best returns; a project generally will not start if its net present value (NPV) is negative.

3.1. The funnel development model

In order to understand how the funnel development model interacts with the engineering design process, it is necessary to initially go into greater detail regarding this framework, especially the project planning phase.

Beyond aiming at delivering successful products, the funnel development model is a framework for the company's *development strategy*, a part of the corporate strategy, which consists in defining the company for tomorrow and controlling whether it is fit for today. The work of the individuals involved in forming/defining the corporate strategy also includes building "a collective view of the future" [43]. A strategy is meant to favour the company's growth and profitability on one hand and to ensure the company's survival on the other. A strategy is defined and re-defined together with the evolution of the company's core competencies, technologies and other external and internal factors, like the market situation and the company's functions. It is more appropriate to see it as the set of goals used to control the company in its environment and to be robust towards "small" environmental changes; after a while, the premises on which the goals have been built are no longer valid, and the strategy is upgraded. A development strategy should aim at developing superior products to ensure profitability, but also *aim at ensuring the company's sustainability and growth* 1) by improving the company's market position or opening new markets, 2) by utilizing effectively the company's core competencies (e.g. specific technical and engineering knowledge and skills that distinguish the company) [44], resources (e.g. the company's existing research results and patents, the existing product and process technologies) and capabilities (e.g. network of suppliers, distribution system — the elements that make the company able to effectively and efficiently realize a product) [37, Definition 3.1.5; 45, Section 15.3; 46], and 3) by capitalizing on the gained experience of product development projects and improving (1) and (2) [40, pp. 28–29].

In order to achieve these goals, it is necessary to have a clear idea of the company's current situation and its environment and to be able to determine the possible directions to take, which means making periodical internal and external analyses [38]. With the internal analysis, the company must get a good grip on what its resources, core competencies and capabilities are, and must try to forecast the different needs of skills, knowledge that will be required in the future for its different functions (engineering, marketing, manufacturing…). With the external analysis, the company acquires a good understanding of the market, competitors, new technologies, regulations…. This helps determine

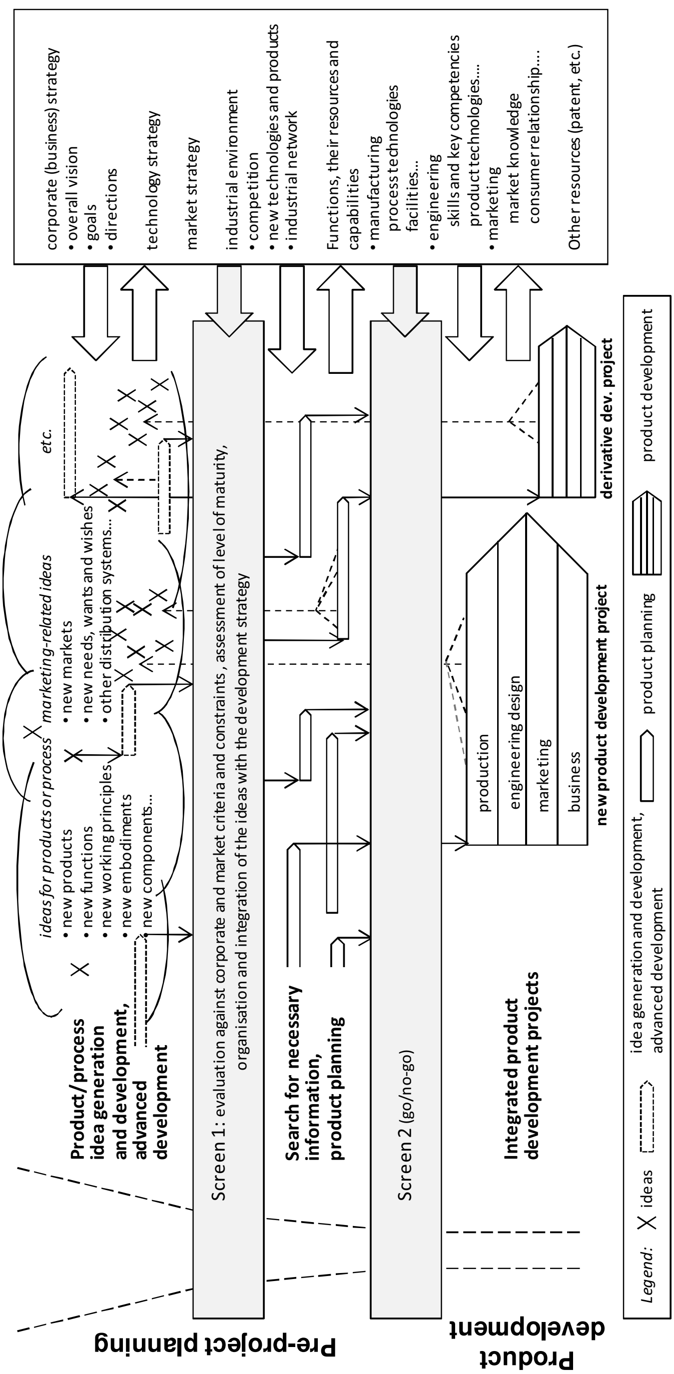

Figure 2. The funnel development framework, from [38] and [40]. On the left, the traditional funnel development representation.

measures, criteria and constraints for projects, and idea review and screening. Different methods are available for the internal and external analyses: SWOT-analysis, five-force analysis [47], functional maps [40]. Examples of measures and criteria are [1, p. 71; 31; 38, pp. 22–34; 40, p. 47]: probability of success, possibility of patent protection, necessary development time and cost — for R&D; time-to-market, expected sales, influence on market share — for marketing; main performances, robustness, maintainability — for engineering design; process knowledge, use of current manufacturing system — for production.

The internal and external analysis contributes also to the development of adequate market and technology strategies. The *technology strategy* objective is "to guide the firm in acquiring, developing, and applying technologies for competitive advantage" [40, p. 36]. That means determining what technologies are critical or of interest, developing adequate technical capabilities (internal and external) and defining research and development investments. During project planning, it is important to take into account the maturity level of the technologies that may be used during subsequent product development projects, as a less mature technology may increase the risk of failure. The *market strategy* helps to determine what products should be offered and when, define the different market segments, and ensure that market changes are transmitted in the development department. It also helps define what kind of product should be developed depending on the market situation, for example new products or variants.

Together with the technology and market strategies, the development strategy can be determined. It gives the goals and directions for the *definition* and *planning* of product (and process) development projects, which will result in the product portfolio and plan.

The different development objectives, long term and short term, also imply different types of projects. Some projects (not product development ones) concern the development of new technologies and/or the acquisition of know-how — the typical R&D projects. Others are variants or adaptations of existing products, focusing on profitability. In between are developments of new products, which will answer to new needs, and probably integrate some new technologies and contribute to develop a new market.

The planning and selection of these projects is done during the pre-project planning phase (or product phase). Ideas are gathered and developed up to a point where a development project can be started. In the literature, the screening of ideas is done during one [1; e.g. 2] or two reviews [e.g. 38; 40] or more [41; 48]. The first screening review consists in 1) evaluating the ideas that fit with the most important criteria issued from internal and external analysis, 2) assessing their level of development or maturity, and 3) organising those ideas and determining for which kind of products they may be useful, i.e. new products or derivatives [40, pp. 126–127].

The second screening concerns the ideas that have been developed into product concept with sufficient information to make a go/no-go evaluation. For Cooper [48] and Smith and Reinertsen [41], an intermediate stage before concept development is the preliminary assessment: preliminary technical feasibility (technical viability of the idea) and preliminary marketing feasibility (prospects for the new product, market segment and size estimations).

The funnel development is presented in Figure 2. The traditional representation (left side of Figure 2) shows the idea refinement process that results in a peculiar project — see [2, p. 14; 40, Chapter 5]. This representation presents on the same axis the idea refinement dimension and the time dimension, which does not show clearly that idea gathering and development happen continuously and in parallel with development projects. Strategies are also developed and adjusted periodically, and so are the internal and external analyses that shape them. This is important as it shows that a development project never starts from scratch. Therefore, we adopt a representation similar to Olsson's [38, p. 15], which distinguishes both dimensions of time and idea refinement.

4. SUMMARY

In this first part of the publication we have presented the main elements and modelling of the generally accepted engineering design process model and its integration within the so-called funnel development model. Based on these findings, in Part II [3] of this publication we will present the issues emanating from this interaction between engineering design and development, and discuss the generic aspect of these design and development models in the light of alternative models.

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