3. The subject, aim and methodology of the dissertation work

This dissertation presents a new cost estimation procedure that can help technology managers to reason about engineering effort. The estimation of engineering effort is a complex but much needed process. Rather than using rules of thumb, engineering cost estimation should be data-driven and persistent.

The subject of this dissertation is the development of a semi-parametric engineering effort estimation procedure for the industrial plant industry, while building on lessons learned in software cost estimation. The driving force is the gap between the reality of organisations involved in engineering cost estimation and available tools and methods. The scope of this dissertation is the identification of the relevant cost drivers and stochastic influences in engineering design cost estimation together with a set of praxis-oriented cost estimation methods.

3.1 Hypotheses and reasoning

The central proposition at the core of this research is:

Hypothesis 1: In practice, nominal effort of an engineering task in the industrial plant industry is not mathematically calculable, because the wealth of engineering solutions can not be described practicably with mathematical methods alone. However, partial algorithmic solutions to weight the nominal estimate are possible and useful.

This statement provides the underlying goals of the intended effort estimation procedure and defines its solution space. To solve the task, a new semi-parametric effort estimation method, a new activity based time keeping method, a method to estimate the project status, and a method to estimate influence factor and effort drivers have been developed. This involved identifying metrics that best capture the effort drivers and influence factors. The different constituents of this approach are pictured below.

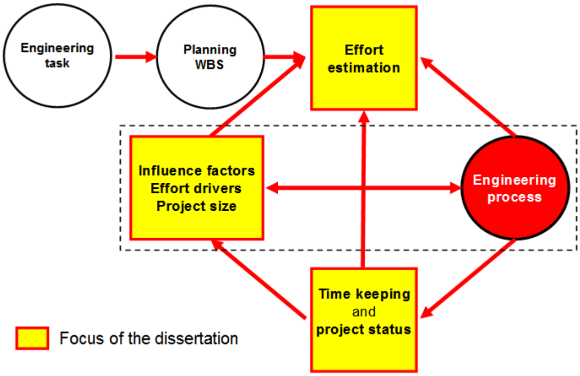

Illustration 1: Constituents of an engineering time estimation procedure

It is important to understand that effort estimation is an ongoing process like going around in a loop. As the engineering task progresses effort estimation needs to be updated and refined.

Looking more closely to its constituent parts, first and foremost it is important to understand the engineering process, it constraints and limitations.

Engineering design is the interdisciplinary process to ensure that the stakeholder needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner. Part of the complexity with engineering design is due to the diversity of companies and products in which engineering design is embedded in practice. The engineering design process is an ambitious undertaking, in which many decisions have to be made concerning processes, products, tools, methods and techniques. It is an iterative process, in which the basic engineering disciplines (mechanical engineering, electrical engineering and automation) are applied to meet customer needs and required functionality [26, 29, 34, 35, 36, 37, 46, 47, 93, 94, 108, 124, 129]. In the context of this dissertation work engineering design enables the creation of industrial plants of different size and complexity.

The primary objective of the engineering task is the digital product (drawings, programs, documents, calculations, etc.) [105, 106].

Furthermore, it is important to distinguish type (mode) of design. Most industrial plants are a combination of new, reused, and modified components. Therefore, a new method must be able to incorporate all three modes.

New respectively original designs are those that have no or only indirect precedents. With original design a new solution principle is determined for a desired system and used to create the design of a product [26, 93, 94].

Variant designs or adaptation designs are those that have a history of well understood direct precedents. The main aim of reused design is to provide the creation of robust designs in less time, with lower engineering effort and production costs.

When utilizing adaptive design an existing design is adapted to changed conditions or functions. As a result the solution principle remains the same but the product will be different so that it can meet the changed functions that have been specified [26, 93, 94].

With variant design the size or arrangement of parts may be varied. However, the desired functions and solution principles are not changed [26, 93, 94].

Consequently, the necessary distinction of the engineering modes leads to the second proposition.

Hypothesis 2: Engineering effort may be engineering type (mode) dependent. Therefore engineering effort estimation must differentiate the three types of the engineering design process (new design, adaptive design, and variant design). Effort drivers and influence factors must be distinguished by the mode of design.

Engineering design is a complex process, it seldom reaches stable equilibrium. The impetus for change comes from a multiplicity of factors. Presumable, some patterns can be predicted. There are minimum and maximum limits beyond which variables cannot move without triggering a response. These limits are normally set by an engineering manager’s knowledge of the engineering process and by project management. This statement triggers another proposition.

Hypothesis 3: Stochastic influence factors are the main causes of cost fluctuations. Errors in nominal effort assessment are subordinate against these fluctuations.

There’s considerable evidence [73, 86, 97, 108] to suggest that engineering design could be seen as a systems whose pieces are connected but only partially connected. To describe this tight–loose combination in terms of scientific manner it is necessary to find and use an appropriate method. To validate this proposal a further proposition has been made.

Hypothesis 4: Influence factors are more or less dependent on each other. The sensitivity analysis method is principally capable to display the dependence structure, as well as to assess the influence factors both qualitatively and quantitatively.

The identification and metrics of stochastic influence factors and effort drivers is pivotal to this work. The influence factors and effort drivers were defined after extensively surveying recent engineering literature (see references in chapter 4.2). Most of the influence factors are stochastic while effort drivers depend on product complexity.

Regression models[3] (see page 3) can be difficult to use to assess influence factors with the conditions of

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[3] Most if not all of the software cost estimation models are based on some form of regression technique. Regression models have a mathematical foundation using equations that characterise the relationships among the different variables

engineering design in the industrial plant industry, because open sources of comparable data sets of past projects are rarely available.

Vester's Method of Sensitivity Analysis (see page 8) with its origin in biological systems makes the assessment of influence factors accessible to a praxis-oriented approach, without getting lost in an endless number of mathematical factors and variables. The method supports integrated thinking, which is hardly achieved without the help of appropriate straightforward instruments.

Keeping in mind that all nominal effort estimation is based on experience and knowledge from previous projects takes one to the assumption that all effort to fulfill a single engineering task should be kept available for comparison and later use. Past performance is the best indicator of future performance. A base of performance data must be collected and analyzed to assist the prediction of future engineering tasks. Therefore a new activity based time keeping method to collect data has been developed.

Hypothesis 5: To collect data on a single engineering task for later comparison (utilising the bottom-up approach) it is necessary to develop and install an activity based time keeping method.

Though, the underlying question that remains to be answered is whether or not the engineering effort for similar engineering tasks is usable or whether it's variation is so great, thus preventing the detection of analogues data. The new estimation procedure will only be able to answer this question when collected data has been analysed (see exploratory research page 9).

Updating cost estimates based on the project's current progress and forecasts of the remaining expenses are important and necessary elements of project controlling. Thus, considering that the precision of effort estimation will increase with progress towards completeness of an engineering task is leading to the final proposition of this dissertation work.

Hypothesis 6: Engineering design is an iterative process. Assessing progress with commonly used start- / finish methods is not practicable for summary working packages. An adaptation of the earned value method must be developed, in which the theoretical completion level is linked with the real project status.

The final logical step in this research reasoning is to shift the focus to verification. The process of verification is twofold: first, a series of data needs to be collected. Second, data needs to be analysed to test the validity of the procedure (see explorative research).

3.1.1 Practice orientation

To achieve the objective of practice orientation, the effort estimation procedure has been developed to provide certain features. Among these is to provide a procedure that is accurate, tailorable to permit ways for individual adjustments, simple with understandable counting rules, well-defined, parsimonious to avoid use of redundant factors or factors which make no appreciable contribution to the results and finally pragmatic.

3.2 Applied methods

A variety of methods have been used in this dissertation work at various levels of depth. Major parts of the dissertation work are based on methods described below:

3.2.1 Activity based time recording

A number of activities typically occur in designing. The timeline can be broken down into several overlapping phases. The descriptive design models[4] [93, 94] typically distinguish between four design phases:

1. Clarification of the task: Collection of information about the requirements to be embodied in the solution but also about the constraints
2. Conceptual design: Search for suitable solution principles and their combination into concept

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[4] The descriptive models are focused on how design is done. In contrast, prescriptive models describe how design should be done

variants
3. Embodiment design: The solution principle respectively the preliminary design
4. Detail design: The final design respectively the digital product (drawings, list of components, etc.)

Activity Based Time (ABT) Recording helps to keep track of the amount of time spent on various tasks, activities and projects. This method has been a useful tool in exploratory research (see chapter 3.2.3) to keep track of the time spend on the various customer projects, activities and tasks. ABT data has also been used in Earned Value Analysis (see chapter 3.2.2) for reviewing project performance [103].

For the exploratory research the method hat to be adapted to engineering design in practice. Data has been collected using an Access data base. Each record includes a primary key, the personal number, the calendar week, the day of recording (Monday through Sunday), the activity code number and the related working hours.

Selectable engineering design activities included not only the four typical design phases but also engineering support to manufacturing, commissioning, customer, suppliers, etc..

3.2.2 Earned Value Analysis and project progress measuring techniques

Earned value analysis is a method that helps to monitor and forecast progress in engineering design projects. It provides a comprehensive set of metrics which help to assess performance and output of an engineering project [15, 103].

In principle EVA compares the amount of work planned and its budget against the amount of work actually carried out, its budget and its actual cost. The measurement of this data can be used to show the current status of a project in terms of cost and time measured against the baseline plan and also to forecast the cost at completion.

Actual percentage of completion (POC) is the value of the work actually done up to a certain point in time, expressed as a percentage. The POC of a project is calculated by summarising the POCs of the individual work packages.

There are several measurement methods: subjective estimate, start-finish, weighted milestone, and proportional. The appropriate method is depending on the type of a work package. Most engineering task work packages have a tangible output respectively a product manufacturing documentation. However, there are some work packages depending on secondary progress with a digital product only, such as layout drawings.

When the start-finish rule is used in progress analysis, e.g. for **part project work packages**, the percentage of completion (POC) increases from 0% to the initial POC (commonly 20% or 50%) at the start date. When the finish date is reached, the POC is 100%. The weighted milestone technique divides the work to be completed for a part project work package into segments, each ending with an observable milestone; it then assigns a value to the achievement of each milestone. The weighted milestone technique is more suitable for longer duration engineering tasks. Proportional measurement is suitable for work packages where cost and services have a constant relationship.

With the secondary proportionality technique, e.g. for a **summary work package**, the performance of a project object is depending upon the progress of other work packages.

The determination of the overall project’s EV is always done by the summarisation of the individual work packages. The EV of a completed work package is always equal to its planned cost. For a work package not being started yet the EV is always zero.

3.2.3 Explorative research of completed engineering design tasks

The term explorative research is often used in the scientific community for issues where little prior research exists. Little is known about effort distribution of engineering tasks. Therefore an explorative research has been performed to identify the range of activities and problems in practice.

Participant observations by the author have been part of the research method. It involved direct observation, group discussion, interviews but also participation as group manager. Although disputed in the scientific community in-situ studies of industrial practice by the use of participant observer and direct observation are common practice. Studies such as those of Hales [61] are examples of in-situ studies.

The exploratory research produced a valuable quantity of data. Data was collected utilizing an activity based time recording (see page 6). In a following step derived data has been researched in greater depth.

3.3.4 Literature review

As a result of the wide range of aspects to be considered, the methodology of the classic scientific literature review and data collection was also utilised for this dissertation work.

The need for a systematic review aroused from the requirement to summarise all existing information about effort drivers in engineering design in a thorough and unbiased manner. Numerous research studies have already been conducted to evaluate cost drivers and influence factors to software cost estimation [25, 56, 61, 69, 70, 91, 95]. Unfortunately, none of those studies were focused to the field of industrial engineering.

My search for scientific literature was based on a manual issue-by-issue search of German and English digital libraries and journals using Google and Google Scholar. The literature included books, industry journals, conference proceedings and dissertations. It should be mentioned that the lack of standardized terminology complicated the search. The search required much effort. This however, does not guarantee completeness. It is possible that I missed relevant literature. Nevertheless, I believe, this is still an accurate method for a literature review.

The qualitative aspect that had to be determined in this work was what drives the costs of an engineering task in an industrial environment. German and English scientific literature in the field of classical engineering has been reviewed in order to find major parameters. Criteria used to test the relevance of the identified influence factors and effort drivers were credibility, transferability and confirm ability. Quantitative data exists only in the form of rules of thumb.

3.3.5 Sensitivity analysis

Sensitivity analysis (see page 8) is an assessment method with emphasis on the observation of large effects caused by minor impacts to a system. The method was used to analyse the linkages between influence factors and to determine the behaviour of each influence factor (see hypothesis 4).

The sensitivity analysis was developed by Vester [126] to handle and manage complex problems with a bio-cybernetic approach. Vester showed that only a few intelligently chosen parameters are sufficient to provide a reliable model for the extremely complex reality. The sensitivity analysis relates each of the finally identified variables to all others. With the means of a systematic cause-and-effect analysis, the foundation for the sensitivity model is developed.

The linkages between the variables will be visualised by the impact matrix. The matrix determines the influence of variables on each other. This is achieved by a process of impact assessment. All of the variables are compared with one another, pair-wise, in the manner of a cross impact matrix. The results are present as Active Sum (AS), Passive Sum (PS), P-value or Q-value. Active Sum is the summation of the grading of the interaction of variables on the horizontal lines while Passive Sum is the summation of the grading of the interaction on the vertical lines.

In the system role each variable is evaluated cybernetically according to its interdependencies. Depending on its pattern of influence, each variable is sent towards the four corners of a diagram which thus reveals its cybernetic role. This maybe a lever (active), a risk factor (critical), a measuring sensor (reactive), an inert element (buffering) or any position in between. The Q Value determines the active and the passive variables and the P Value determines the critical and the buffering variables.

However, to deliver numerical results for the effort estimation the sensitivity analysis had to be adapted by the author.

4. Major results and discussion

Three topics encompass the major results of this dissertation work. The first topic comprises the results of an exploratory research. The second topic deals with the identification and metrics of effort drivers and influence factors. However, this topic is embedded in topic three, the development of a new practice-oriented procedure for engineering time estimation.

4.1 Exploratory research of completed engineering design tasks

Five engineering design projects have been investigated using an explorative research method (for definition see page 7) to find answers to the research question of what factors have been the main causes for the projects to deviate from original planning.

The engineering design took place during the period from March 2003 until December 2005. The data set with 2.327 records is quite large relative to many other published studies, especially when taken into account that it took almost 32 months to collect data. However, it is still small in terms of what researchers might like to have in order to assure that the results are robust.

All five projects were designed by the same interdisciplinary team consisting of mechanical engineering, electrical engineering and automation technology.

The main estimation techniques used across the five projects were analogy and expert judgement with varying degrees of formality and structure. Nominal effort estimate for variant design and adaptation design has been estimated with the help of a bottom-up approach (see page 3) utilising historical data stored in an Excel sheet. Engineering effort estimation required for new design was based on expert opinion (see page 2). It has been estimated by the sales engineer and the two work group managers. Nominal effort has not been weighted by complexity and size.

In sum, over-optimistic nominal effort estimates were on obvious reason for cost overrun (for numbers see illustration 7). However, over-optimism does not necessarily describe properly the real reason. As responsible engineering design manager I have experienced that many projects originally had realistic but higher cost estimates. Cost reduction pressure from sales blaming competition lead to estimates in hindsight reported as over-optimistic.

Activity based time recording (see page 6) allowed deep insight and a detailed analysis of the engineering design process (see Hypothesis 3). An example of a time course analysis is illustrated below. Consecutive analysis confirmed engineering design as an iterative process with overlapping phases (see illustration 2).

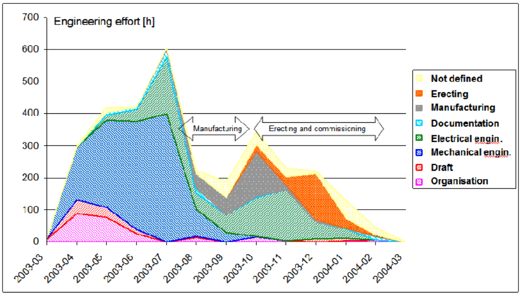

Illustration 2: Example of a time course analysis

The share of engineering design types (variant, adaptation and new design) corresponded with those known from engineering literature [37, 94]. Notably, already minor engineering type share differences had a deep impact on overall engineering effort. Different design types lead to different constraints (Hypothesis 2). A higher proportion of variant design had a clearly visible stabilizing impact on overall engineering effort.

All five projects had a two-level WBS, where the higher level was the assembly level with a summary work package and the lower level several part project work packages (for definition of work package see page 1).

For the total engineering effort expenditure of all part project work packages the nominal cost estimate matched very well with the reality. The average of all five analysed projects showed a discrepancy of only -1%, with a minimum of - 14% and a maximum of +7%. However, a closer look at the individual work packages was less positive. The variation increases if the functional areas are considered separately. For the single work packages the variation between cost estimate and reality discrepancy reached a minimum of – 10% and a maximum of +56%.

In comparison with part project work packages, engineering effort overruns for summary work packages were significantly higher. In particular a somewhat higher proportion of new design led to an exponential increase of all quality assurance activities by engineering.

For the summary work packages the deviation was extremely high. As expected (see Hypothesis 6), the effect of stochastic influences was very strong. The deviations of the summary work packages amounted to an average of -119%, with a minimum of -257% and a maximum of -7%. These variations cannot be explained without further detailed analysis of the stochastic influences. The fact that accuracy deteriorates when one looks at more detailed levels indicates that looking at the estimation accuracy at lower levels is appropriate. For now, at the level of the individual work packages one cannot speak of secure effort estimations.

Time shares of the various activities of the engineering design process have been highly inconsistent. It was not possible to conclude from the time-expenditure of a finished activity to the time-expenditure of an activity still to be completed (see Hypothesis 5).

Apart from number and complexity of interfaces, cost drivers could only be guessed but not confirmed. The reason for this is likely the desired uniformity of the analysed projects. An equal among equals can not be distinguished.

Solving an engineering design problem is obviously a contingent process and the solution is subject to unforeseen complications and changes as it develops. Each engineering job performed differently because many disturbing influences could not be avoided. As a matter of fact, engineering effort was heavily affected by stochastic influences (see Hypothesis 4). However, only a small part of the influence factors could be identified with the help of the activity based time recording, since their causes are often hidden and only revealed themselves in retrospect.

With the exception of services provided by engineering and order sequence, all other influence factors were already known from literature review (see page 8). Services provided by engineering required a large share of total engineering effort. Therefore engineering effort estimation must take the product life cycle into account, especially in the manufacturing and erecting phases.

The reasons for cost overruns have been complex. A problem when analyzing reasons for cost overruns has been that many designers have been biased and affected by selective memory. All engineers had a tendency to over-report causes that have been outside their responsibility, especially customer related problems. Thus, the top-rated causes were requests for change by customers, followed by overlooked requirements and poor requirement understanding mainly caused by customer’s foreign languages. Three of five projects have been troubled with quality problems and consecutive serious cost overruns due to poor requirements understanding.

The influence factors personnel capability (6), team capability (7), supporting management processes (8), IT-tool support (9), and communication (11) did not change. Obviously, these influence factors mirror the totality of qualifications and operational organization.

Research also revealed that the assignment of influence factors to a common group is often very difficult, because many influence factors effect each other and the causes and effects are hardly distinguishable (see Hypothesis 4).

4.2 A new practice-oriented procedure for engineering effort estimation

An important part of developing a new semi-parametric engineering effort estimation procedure was the appraisal of past work in related areas [1, 10, 12, 21, 25, 123]. Thus COCOMO II (see page 3) was a natural starting point which provided a useful and mature framework for the development of a new semi-parametric procedure.

As shown in Illustration 3, the proposed semi-parametric cost estimation procedure is designed as a series of logical steps with iterations as the project progresses:

1. In order for the estimate to attain any degree of accuracy, it is important that the requirements are defined and documented prior to the estimate. During the engineering design process, many projects experience change in requirements up to 25%
2. The engineering task must be decomposed into working packages (see page 1), respectively a list of estimable tasks
3. **Nominal effort**: For each working packed the type of engineering design has to be determined (Hypothesis 2). For variant and adaptation design the nominal effort estimation will be taken out of a data base. New design estimation will be based on Three Point Estimation technique (see page 2). Finally, all estimates will be added into a compound.
4. **Weighting of nominal effort**: Effort drivers and influence factor must be identified. This requires a strong understanding of the engineering environment and the factors that affect engineering effort. For each effort driver or influence factor a metric must be defined.
5. Plausibility will have to be checked utilizing analogies (see page 2). The procedure involves collecting relevant historical data, and relating it to the final product to be estimated through the use of data analysis and mathematical techniques.
6. As the project progresses the sequence must be iterated. Engineering projects are typically characterised by changes in scope and requirements, the impact of these changes can vary phenomenally depending on the time at which the change is introduced.

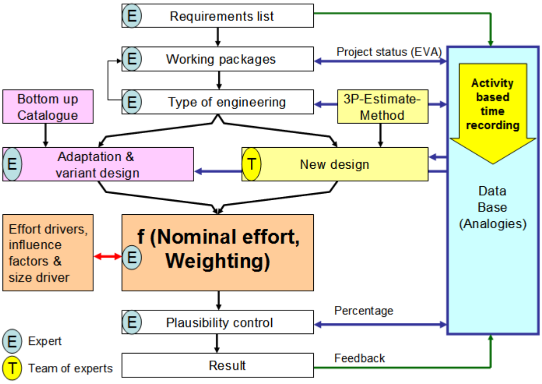

Illustration 3: Engineering time estimation procedure

Core of the semi-parametric procedure is the equitation for weighting nominal effort (Hypothesis 1). Similar to parametric methods of software cost estimation [10, 123] the equitation comprises three different types of parameters: additive, multiplicative, and exponential.

$$A = (C \cdot \left(A_{VarKo} + A_{AnpKo} + A_{NeuKo} + AT\right)^{K} \cdot \prod_{i=1}^{n} EF_i)^{GF}$$

These parameters represent a calibration factor (C), the nominal size (A_{VarKo}, A_{AnpKo}, A_{NeuKo}, AT)[5], a

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[5] VarKo – variant design; AnpKo – adaptation design; NeuKo – new design; AT – additive effort driver

complexity factor as the sum of five effort drivers (K), twelve influence factors (EF), and one size driver (GF).

The general rationale for whether a factor is additive, exponential, or multiplicative comes from the criteria:

- Nominal size is additive because it has a local effect on the engineering task.
- Influence factors are multiplicative because they have a global effect across the overall engineering task.
- Effort drivers and the size driver are exponential because they have both a global effect and an emergent effect for larger engineering tasks [123].

On the surface parametric software cost estimation methods appear to be alike. However, there are fundamental differences between them and the proposed engineering time estimation procedure that will be highlighted hereafter.

4.2.1 Nominal Size

Given that size is the principal determinant of effort, an accurate nominal size estimate is crucial to a good estimation. In contrast to software cost estimation methods, where size estimate is derived from an assessment of transactions and data functions (e.g. function points), extensive literature review did not provide more detailed information on what generic characteristics could determine the size of the engineering design effort in non-software projects.

For industrial plant design, it can be argued that parametric effort estimation can not even at it very best provide estimates that can be considered reasonably accurate. There are many reasons why parametric estimation techniques fail to perform. Just to list a few of them:

- the essence of software development is fundamentally different from engineering design of industrial plants. Where as software development could be seen as one-dimensional[6], engineering design has to cope with no less than 28 dimensions [93, 94], e.g. volume, weight, material, temperature, design for manufacturing, etc.,
- the essence of one industrial plant could be fundamentally different from another industrial plant,
- changes in technology that are not fully understood in terms of their effect on engineering effort.

Therefore, as proposed in hypothesis 1, it must be concluded that there is no purely mathematical estimation method that could solely calculate the engineering effort. Without experience all known methods and procedures are worthless.

Recognizing that companies do not constantly reinvent the wheel every time a new project comes along, there is a need for an approach that capitalizes on the organisational memory. Therefore, the ability to create a simple database of past engineering project data will be the key to success. Proofed estimates of nominal effort will be stored in the data-base for later use. Thus, nominal size estimation is based on the bottom-up approach (see page 3). This approach capitalizes on experience and standardization. When a design reuses a module, we only count a fraction of the design effort for the original new design. The rationale is that, in accordance with the principles of modular design, the effort required to design and verify a new design is a one-time cost. Once a module is designed and verified, it can be reused elsewhere with less effort.

Nevertheless, it has to be kept in mind that expert estimations (see page 2) depend on the knowledge, capability and objectivity of the estimator, who may be biased, optimistic, pessimistic, or unfamiliar with key aspects of the project.

4.2.2 Effort drivers (complexity factor)

The effort drivers are the characteristics of a product or item that have major effects on its cost. Each effort driver models different phenomena. The selection of effort drivers is based on the rationale that they are a significant source of variation on an engineering project's effort. Because the relationship

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[6] In contrast to engineering design, software engineering does not have to deal with physical dimensions

between engineering efforts for single engineering task to projects with higher complexity is not linear, data collected on single engineering tasks will be systematically underestimated. Therefore intuitively[7] a complexity factor (K), as the sum of the effort drivers (AT), had to be introduced.

$$K = 1 + 0{,}001 \times \sum_{i=1}^{i} AT_i$$

Similar to metrics in COCOMO II (see page 3) each effort driver has a rating level, ranging from very low to extra high.

Product complexity (AT1): A typical industrial plant may have hundreds of requirements. Naturally, not all requirements are demanding or have the same level of complexity. Some may be more complex than others based on how well they are specified and how much they overlap with other requirements. Product complexity is mainly driven by the number of different modules and the different ways of connecting these modules. Modular, hierarchical structuring can reduce product complexity [10, 37, 108, 123, 126, 135]. Range of product complexity from very low to very high is 0,0 to 10,0.

Product maturity (AT2) describes the readiness of the product or its key technologies for operational use. This effort driver is primarily due to the fact that even small modifications may generate disproportionately large costs [10,]. Although often variant design can be directly reused, it can not be expected to function in the same way if it is directly scaled or if elements of it are reused in different systems. Range of product maturity from very low to very high is 0,0 to 10,0. Very low means no previous experience; Extra high means that the organisation is completely familiar with this application.

Number and complexity of interfaces (AT3) represents the number of shared major physical and logical boundaries between the entire or a part of an industrial plant (internal interfaces) and those external to the industrial plant (external interfaces). Both the quantity and complexity of interfaces require more engineering effort and increase the overall complexity [123]. Range of number and complexity of interfaces very low to very high is 0,0 to 2,5. Additionally, this effort driver also has an additive part (AT in the equitation formula).

Level of automation (AT4) represents the number and complexity of automated operational scenarios that an industrial plant is specified to satisfy [123]. Automation can vary across a continuum of levels, from the lowest level of fully manual performance to the highest level of full automation. Each level carries with it increased responsibilities for the industrial plant, and reduced opportunity for human intervention. Range of level of automation from very low to very high is 0,0 to 5,0. Additionally, this effort driver also has an additive part (AT in the equitation formula).

Share of subcontractors (AT5): The make-or-buy question represents a fundamental dilemma faced by many companies. Industrial plants are becoming increasingly complex. Companies have finite resources and may not be able to afford to have all activities in-house. Small numbers of subcontractors enables industrial plant manufacturers to profit from efficiencies due to mutual adaptations. However, in isolation subcontracting can have unexpected side effects. External activity must be coordinated by engineering to become a part of the whole [71]. Increased coordination can primarily counteract potential savings as a result of communication overheads. Range of share of sub-suppliers from very low to very high is 0,0 to 2,5.

Example: The exponential complexity factor ranges from 1,00 (very low) and 1,03 (extremely high). An engineering task with a nominal effort of 6.000 hours and a complexity factor with the maximum of 1+0,001 x (10+10+2,5+5+2,5) = 1,03 will be weighted to 7.789 hours.

4.2.3 Influence factors

With the help of both literatures review (see page 8) and exploratory research (see page 7), the most

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[7] Although the equitation appears to be identical to COCOMO II its first multiplier is 10 times smaller (0,001 instead of 0,01)

important influence factors have been identified and evaluated.

Stochastic influences are the main causes of effort fluctuations (Hypothesis 2). Some of these influences could substantially impair engineering performance and may make original cost estimations obsolete. Change may appear from a multiplicity of factors. An example is the level of customer expectations. If the customer wants a highly flexible product, it will make the design task a lot more complex than if the customer had no such expectations. These stochastic variations could appear in both positive or in negative direction. For the project manager, the critical issue is to know what to control and what to let go.

The identification of risks is often dampened by the tendency of humans to be overly optimistic about their ability to perform on schedule and on budget. This is especially true in the early stages of project planning [123]. With caution it can be concluded that most initial effort estimations do not include risk.

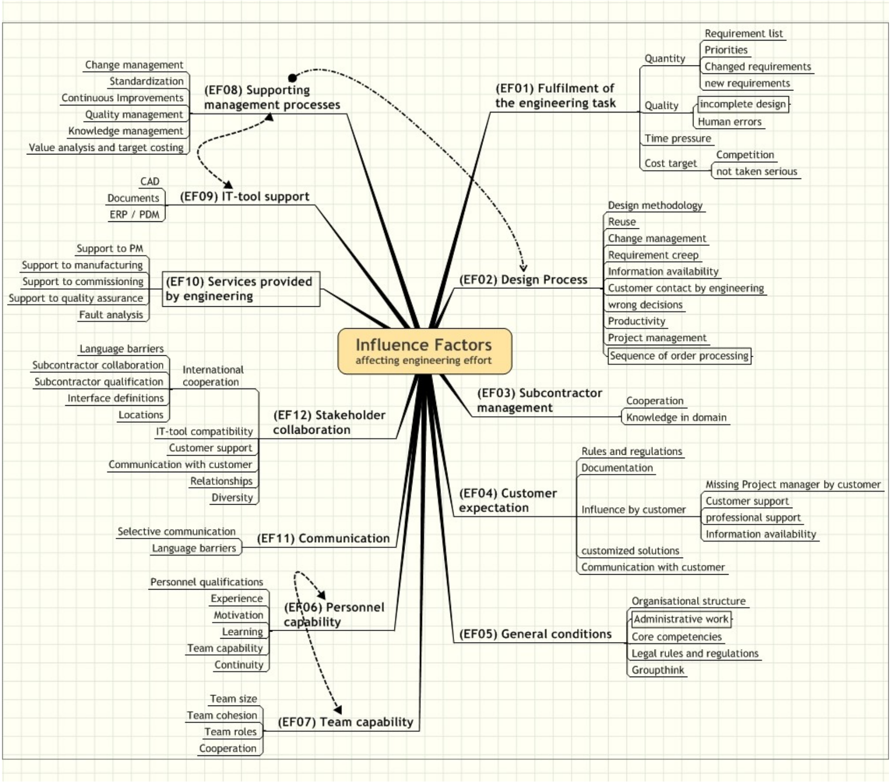


Illustration 4: Influence factors

Most influence factors have multi-attribute parameters which represent a coherent group of variables (see illustration 4). An influence factor may increase or decrease the nominal effort of an engineering task.

Fulfilment of the engineering task (EF1) represents the difficulty and criticality of satisfying the key performance parameters of the engineering task namely quantity, quality, time-pressure and cost-target. Every careful project manager has to balance these four key factors against each other. The four key performance factors unavoidably compete with each other for the resources of an engineering design project. Hence, every additional consumption of one resource leads to reduction in the availability of other resources. This effect is known as the devils square of project management [10, 17, 21, 26, 29, 34, 35, 37, 45, 47, 53, 56, 61, 94, 95, 119, 123, 124, 128].

A systematic approach is seen as helpful to the engineering designer to complete a complex engineering design task. **Engineering design process** (EF2) represents the proficiency and use of methods to perform the engineering design process. The design process can have a significant effect on productivity. This influence factor includes engineering design methodology (e.g. as characterised in VDI 2221), novelty of the process, requirement creep including Parkinson's law, information availability, customer contact, insufficient decisions and productivity [13, 17, 25, 26, 35, 94].

An subcontractor is a organisation that contracts with the general contractor to design a component of the industrial plant. The purpose of subcontractor management is to select qualified subcontractors and manage them effectively. **Supplier management** (EF3) respectively subcontractor management represents the degree of familiarity and cooperation with the key suppliers and technical understanding of supplied key parts [10, 12, 71]. Knowledge of the subcontractor's domain is essential, because ultimately the general contractor is responsible for the subcontractor's work.

The engineering process should include opportunities for customers' interactions during engineering design, manufacturing, and acceptance to ensure that needs and requirements will be fully understood. **Fulfillment of customer expectations** (EF4) represents customer's satisfaction with the design process, rules and regulations set by customers, documentation requirements, and the customer's degree of influence to technical solution [35, 96].

General conditions (EF5) represent appropriate organisational structure, core competence, dependence on legal rules and regulations and groupthink. Most of these factors will not change very often. However, even slight changes, for example a change in a legal regulation, may seriously affect the engineering effort to be spent [35, 112].

Engineering is an intellectual activity, the most important ingredient for producing high-quality digital products efficiently is the engineering designer. The engineering designer has to cope with a wide range of activities within a wide range of circumstances. **Personnel capability** (EF6) represents the level of personnel qualification, capability and continuity, as well as personnel experience with the relevant engineering domains, applications, language, and engineering tools [26, 29, 46, 56, 58, 84, 87, 129].

Team capability (EF7) represents the level of team qualification, shared vision, cooperation and team cohesion. In software development, it is well known that different teams have different capabilities and productivities. Large teams are likely to have a mix of abilities and experience and therefore will have 'average' productivity. In small teams, however, overall productivity is mostly dependent on individual aptitudes and abilities [35, 86, 93]. However, it is most likely that the team capability factor is constant per design group, and needs to be adjusted on a per company or design team basis.

The need to incorporate quality during the design phase has created a need for a more structured approach to engineering design. **Supporting management processes** (EF8) represents the proficiency and use of methods, e.g. FMEA, QFD, 8D, etc., to support the engineering design process [34, 35, 36, 37, 41, 68, 81, 128, 135].

Computers, as tools for design, modelling, information processing and communication have greatly increased human productivity and knowledge. **IT-tool support** (EF9) represents the efficiency of IT-tools, e.g. CAD- systems. It is imperative to ensure that engineers are not forced to suffer with antiquated computer equipment, which can impede their ability to complete their job responsibilities efficiently [72, 94, 101, 105, 106].

There are three main phases in an industrial plant life cycle directly related to engineering effort estimation: the engineering design phase, the manufacturing phase and the erecting & commissioning phase. **Services provided by engineering** (EF10) represent specific services provided by engineering. These include support to the project manager, assistance to manufacturing, commissioning, etc.. Depending on qualification and experience of others involved, engineering may be obliged to provide support.

Communication (EF11) represents the process of transmitting information, ideas, thoughts, opinions and plans between the various parts of an organization. Inappropriate or faulty communication among employees or between managers and their subordinates is the major cause of conflict and low morale at work [10, 123].

Stakeholder collaboration (EF12) represents heterogeneity and diversity of stakeholders, their location and possible need to travel. Difficulties in stakeholder collaboration may arise from differences in stakeholder objectives and cultures; difficulties in reconciling objectives; and stakeholder’s lack of experience and familiarity in operating as a team [10, 56, 123].

These twelve influence factors will be the variables in the adapted sensitivity analysis (see next chapter).

It has to be mentioned that algorithmic approaches that uses variables like influence factors to predict effort have received a lot of critique. Correlations that the variables might demonstrate in empirical investigations are not entirely causal (Hypothesis 4).

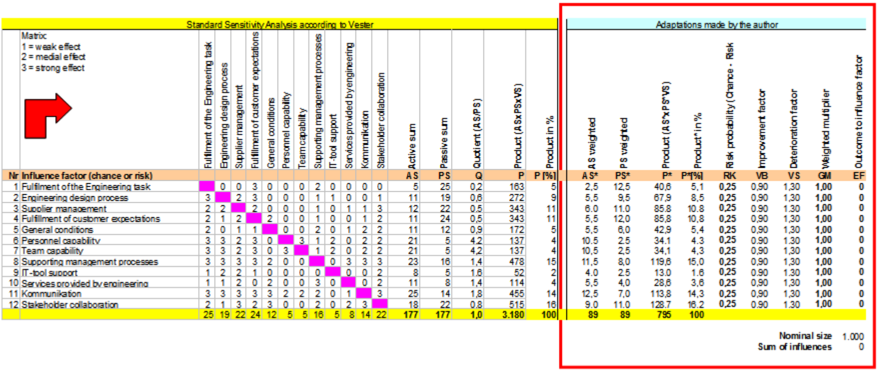
It is evident that the above listed influence factors have been derived by some level of subjectivity. Although the effort estimation procedure is aimed to be semi-parametric it is still an expert estimation (see page 2). In this context it is my belief that subjectivity although often seen as a threat to the reliability of estimates - can also be an opportunity. “Expert subjectivity” allows for a reduction in the number of effort drivers as well as for factors that are difficult to measure. Therefore, with wary it can be concluded that subjectivity coming from experts may in proper circumstances be used as an adjustment factor for effort estimation models.

4.2.4 Sensitivity analysis for the numerical assessment of influence factors

The list of influence factors may be considered as identified chances or risks [73]. The occurrence of an influence factor is quantifiable by probability. Risk (R) or chance (C) has a value of severity. Consequently risk or chance can be seen as the product of probability of occurrence (P) and the extent of deviations (A).

$$R = P(R) \times A(R) \text{ or } C = P(C) \times A(C)$$

To deliver countable numbers representing influence in the effort estimation equitation, the method of sensitivity analysis (see page 8) had to be adapted.



Standard Sensitivity Analysis according to Vester																		
	Matrix 1 = weak effect 2 = medial effect 3 = strong effect	Fulfilment of the Engineering task	Engineering design process	Supplier management	Fulfillment of customer expectations	General conditions	Personnel capability	Team capability	Supporting management processes	IT-tool support	Services provided by engineering	Kommunikation	Stakeholder collaboration	Active sum	Passive sum	Quotient (AS/PS)	Product (ASxPSxVS)	Product in %
Nr	Influence factor (chance or risk)													AS	PS	Q	P	P [%]
1	Fulfilment of the Engineering task	🟪	0	0	3	0	0	0	2	0	0	0	0	5	25	0,2	163	5
2	Engineering design process	3	🟪	2	3	0	0	0	1	1	0	0	1	11	19	0,6	272	9
3	Supplier management	2	2	🟪	2	0	0	0	1	0	1	1	3	12	22	0.5	343	11
4	Fulfillment of customer expectations	2	1	2	🟪	2	0	0	1	0	0	1	2	11	24	0,5	343	11
5	General conditions	2	0	1	1	🟪	0	0	2	0	1	2	2	11	12	0,9	172	5
6	Personnel capability	3	3	2	3	0	🟪	3	1	2	0	2	2	21	5	4.2	137	4
7	Team capability	3	3	2	3	0	3	🟪	1	2	0	2	2	21	5	4,2	137	4
8	Supporting management processes	3	3	3	3	2	0	0	🟪	0	3	3	3	23	16	1,4	478	15
9	IT-tool support	1	2	2	1	0	0	0	0	🟪	0	0	2	8	5	1.6	52	2
10	Services provided by engineering	1	1	2	0	2	0	0	3	0	🟪	0	2	11	8	1,4	114	4
11	Kommunikation	3	3	3	3	3	2	2	2	0	1	🟪	3	25	14	1,8	455	14
12	Stakeholder collaboration	2	1	3	2	3	0	0	2	0	2	3	🟪	18	22	0.8	515	16
		25	19	22	24	12	5	5	16	5	8	14	22	177	177	1,0	3.180	100

Adaptations made by the author										
		AS weighted	PS weighted	Product (AS*xPS*VS)	Product* in %	Risk probability (Chance - Risk	Improvement factor	Deterioration factor	Weighted multiplier	Outcome to influence factor
Nr	Influence factor (chance or risk)	AS*	PS*	P*	P*[%]	RK	VB	VS	GM	EF
1	Fulfilment of the Engineering task	2,5	12,5	40,6	5,1	0,25	0,90	1,30	1,00	0
2	Engineering design process	5,5	9,5	67,9	8,5	0,25	0,90	1,30	1,00	0
3	Supplier management	6.0	11.0	85.8	10.8	0,25	0.90	1.30	1,00	0
4	Fulfillment of customer expectations	5,5	12,0	85,8	10,8	0,25	0,90	1,30	1,00	0
5	General conditions	5,5	6,0	42,9	5,4	0,25	0,90	1,30	1,00	0
6	Personnel capability	10.5	2.5	34.1	4.3	0,25	0.90	1.30	1,00	0
7	Team capability	10,5	2,5	34,1	4,3	0,25	0,90	1,30	1,00	0
8	Supporting management processes	11,5	8,0	119,6	15,0	0,25	0,90	1,30	1,00	0
9	IT-tool support	4.0	2.5	13.0	1.6	0,25	0.90	1.30	1,00	0
10	Services provided by engineering	5,5	4,0	28,6	3,6	0,25	0,90	1,30	1,00	0
11	Kommunikation	12,5	7,0	113,8	14,3	0,25	0,90	1,30	1,00	0
12	Stakeholder collaboration	9.0	11.0	128.7	16.2	0,25	0.90	1.30	1,00	0
		89	89	795	100					

Nominal size 1.000
Sum of influences 0

Illustration 5: Adapted Sensitivity Analysis

Core of the sensitivity analysis method (see page 8) is the impact matrix. The matrix describes the level of interactions between influence factors (Hypothesis 4). For this purpose a set of influence factors appears in a cross-impact matrix where the effect of every variable upon any other will be evaluated.

With a rating scale ranging from 0 (no effect) to 3 (strong effect, the matrix determines the effects of variables on each other. The result is a set of values for of each influence factor. These values include the active sum (AS), the passive sum (PS), the quotient (Q) and the product (P). According to its pattern of influence, each influence factor is between 'active' and 'reactive' on one hand and between 'critical' and 'buffering' on the other [126]. The size of the circles is determined by the product (P) of an influence factor.

It is important to look at the mode of action diagram with the knowledge in mind that the borderlines between the four quadrants are not strict. Moreover, the diagram gives only an idea of the behaviour of the variables. It is only a qualitative tool.

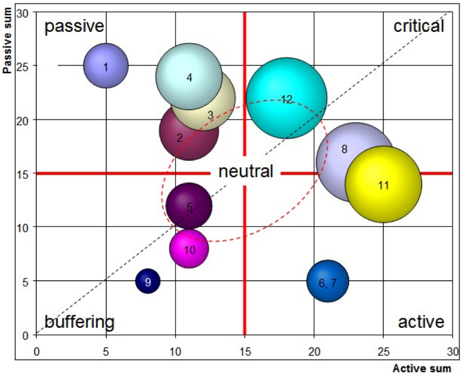


Illustration 6: Mode of action of influence factors

Active variables, e.g. personnel capability (6) and team capability (7) strongly affect other variables but are barely affected by itself. Changes and activities that affect variables located in this field have great effects on the systems (engineering) behaviour. This behavior is in full compliance with scientific literature [26, 29, 46, 58, 84, 87, 129] and many managers experience.

Critical variables, e.g. supporting management processes (8), communication (11) and stakeholder collaboration (12) strongly affect other variables and are strongly affected by itself. Changes and new developments of the variables located in that field can occur easily. If changes occur they will greatly influence other factors, that is the system as a whole and thus also the critical variable itself. The effects of developments may follow each other in quick successions. Any interventions must therefore be particularly carefully examined to determine their entire cross linkages before the action is taken. On the other hand, the critical variable is a very good lever to start things moving when the situation appears to be “stuck in the mud”.

Passive variable, e.g. fulfilment of the engineering task (1), engineering design process (2), supplier management (3), fulfilment of customer expectations (4) affect other variables barely but are strongly affected by itself. The disadvantage with a passive variable is that its effects on other variables first become noticeable when extreme states occur. This causes that the necessary regulation may perhaps come too late. This again corresponds with findings in scientific engineering literature [47, 53, 61, 94, 119, 128].

Buffer or inert variables, e.g. general conditions (5), IT-tool support (9), services provided by engineering (10) affect other variables barely and are barely affected by itself. A variable located in that field can be scarcely influenced by the other factors. Decisions concerning those variables are less critical. It is confirmed that the effect of IT-tool support is usually overestimated [46, 61, 66, 69, 72, 108]. Usually, general conditions cannot be influenced by engineering.

The product (P) expresses the impact of an influence factor on the system (engineering process) with 100% participation. In practice this will rarely be the case, because negative impact of an influence factor will be limited by management activities.

The occurrence probability of an influence factor is expressed with the risk index (RK). Since the matrix is two-dimensional the weighted sum of the product (P*) will be multiplied by the square root of the risk index (RK). Since the chances to shorten engineering effort are smaller than the risks, a risk index of 0.25 to will display the balance of opportunities and risks. Therefore the multiplier of the nominal effort with a risk index of 0,25 is =1 (no influence).

With a risk index of 0,0 the nominal effort will be improved by the improvement factor (VB), for example 0,9. With a risk index of 1,0 the nominal effort will we worsened by the deterioration factor (VS), for example 1,3.

Either result will be displayed as outcome to influence factor (EF) with the nominal size as basis. It is important to understand that a change of one influence factor will also change all other influence factors according to the relation in the impact matrix, because sensitivity analysis relates each of the influence factors to all the others.

The multiplier (M) on nominal effort arises from the equation:

$$M = P * \cdot \frac{VS - VB}{P} + VB$$

The risk factor (RF) allows two time-dependent perspectives. From the retroactive perspective the risk factor is a measure of the impact on nominal effort. In the advance-sighted view, the risk factor is a measure of probability of occurrence. For the period of the engineering task the risk factor stands for a mixture of both perspectives.

In contrast to algorithmic methods for software effort estimation, both improvement and deterioration factors have to be specifically determined. There is no generally valid metric, although both limits and range between the two factors somehow appear to be generic[8].

4.2.5 Size driver

Empirical evidence verifies the hypothesis that engineering effort exhibits a diseconomy of scale [17, 21, 25, 69, 91]. Larger engineering tasks will require proportionally more engineering effort than smaller engineering tasks. This is generally due to two main factors: growth of interpersonal communications overhead and growth of large-system integration overhead. Larger projects will have more personnel, and thus more interpersonal communications paths consuming overhead.

Although the size driver is exponential to the nominal value, its influence is relatively moderate because the size driver’s value, with a range between 1,003 and 1,023, is low.

4.2.6 Considering project progress – closing the loop

During the planning phase (see page 1) we plan how we want the project to progress. However, errors in planning and unforeseen events may cause the project to vary from original planning and effort estimate [15]. Therefore we must constantly monitor actual project progress and compare it with planning. This enables the project manager to identify cost and schedule variances and to take appropriate action.

As emphasised in Illustration 1, engineering effort estimation is always depending on progress. Only the very first effort estimation starts wit a clear paper.

Earned Value Analysis (see page 7) is a way to make the progress of a project measurable and predictable at any stage. In principle EVA compares the amount of work planned and its budget against the amount of work actually carried out, its budget and its actual cost. The measurement of this data can be used to show the current status of a project in terms of cost and time measured against the baseline plan and also to forecast cost at completion.

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[8] Explorative research revealed that all influence factors vary between 0,9 to 1,3 of nominal effort

In engineering the unsolved problem with measures that rely on the amount produced is that they take no account of quality characteristics such as reliability and maintainability. Explorative research delivered many examples of this problem.

4.4 Validation

The six hypotheses of this work were tested through the use of the scientific methods and analysis of data to determine their validity with the aim of developing a meaningful solution. For now, the belief is that the significant effort drivers and influence factors have been identified. The new methods as part of the new practice-oriented estimation procedure proofed themselves as useful and practice-oriented. In sum, the new procedure consistently fulfilled the requirements for engineering effort estimation for the industrial plant industry.

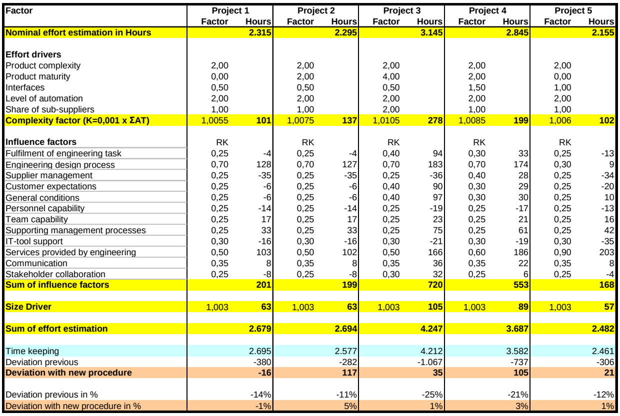
Through empirical validation with real evidence (see illustration 7) it has been demonstrated that the measures proposed served the purpose they were defined for and that they have been useful in practice. The new effort estimation procedure has been tested and validated utilizing data of five exploratory studies[9].

The complexity factor, respectively the values of five effort drivers have been rather low (1,0055 to 1,0105) and did not critically impact the overall effort estimation. However, the effort drivers still reflected the fact that engineering effort increased exponential with project size.

For the given size of the five examples, the size driver proofed to be much less important and could have been neglected (included to the complexity factor).

The effects of the twelve stochastic influence factors could be calculated with good accuracy. Influence factors have been the main causes of engineering effort deviations (Hypothesis 3). However it should be mentioned, that inputs may have been subjective and that all metrics have been calibrated to fit the past.

The effort estimation accuracy for the five projects was surprisingly uniform. This is remarkable, because available evidence on software cost estimation models does not suggest that the estimation accuracy improves with use of formal estimation models [69].



Factor	**Project 1**		**Project 2**		**Project 3**		**Project 4**		**Project 5**	
	Factor	**Hours**	**Factor**	**Hours**	**Factor**	**Hours**	**Factor**	**Hours**	**Factor**	**Hours**
Nominal effort estimation in Hours		**2.315**		**2.295**		**3.145**		**2.845**		**2.155**
Effort drivers										
Product complexity	2,00		2,00		2,00		2,00		2,00	
Product maturity	0,00		2,00		4,00		2,00		0,00	
Interfaces	0,50		0,50		0,50		1,50		1,00	
Level of automation	2,00		2,00		2,00		2,00		2,00	
Share of sub-suppliers	1,00		1,00		2,00		1,00		1,00	
Complexity factor (K=0,001 x ΣAT)	1,0055	**101**	1,0075	**137**	1,0105	**278**	1,0085	**199**	1,006	**102**
Influence factors	RK		RK		RK		RK		RK	
Fulfilment of engineering task	0,25	-4	0,25	-4	0,40	94	0,30	33	0,25	-13
Engineering design process	0,70	128	0,70	127	0,70	183	0,70	174	0,30	9
Supplier management	0,25	-35	0,25	-35	0,25	-36	0,40	28	0,25	-34
Customer expectations	0,25	-6	0,25	-6	0,40	90	0,30	29	0,25	-20
General conditions	0,25	-6	0,25	-6	0,40	97	0,30	30	0,25	10
Personnel capability	0,25	-14	0,25	-14	0,25	-19	0,25	-17	0,25	-13
Team capability	0,25	17	0,25	17	0,25	23	0,25	21	0,25	16
Supporting management processes	0,25	33	0,25	33	0,25	75	0,25	61	0,25	42
IT-tool support	0,30	-16	0,30	-16	0,30	-21	0,30	-19	0,30	-35
Services provided by engineering	0,50	103	0,50	102	0,50	166	0,60	186	0,90	203
Communication	0,35	8	0,35	8	0,35	36	0,35	22	0,35	8
Stakeholder collaboration	0,25	-8	0,25	-8	0,30	32	0,25	6	0,25	-4
Sum of influence factors		**201**		**199**		**720**		**553**		**168**
Size Driver	1,003	**63**	1,003	**63**	1,003	**105**	1,003	**89**	1,003	**57**
Sum of effort estimation		**2.679**		**2.694**		**4.247**		**3.687**		**2.482**
Time keeping		2.695		2.577		4.212		3.582		2.461
Deviation previous		-380		-282		-1.067		-737		-306
Deviation with new procedure		**-16**		**117**		**35**		**105**		**21**
Deviation previous in %		-14%		-11%		-25%		-21%		-12%
Deviation with new procedure in %		-1%		5%		1%		3%		1%

Illustration 7: Validation

However, even when all results were consistent and reproducible, there is a clear need to gather further empirical data. Moreover it is evident that the presented effort estimation procedure is characterized by some level of subjectivity. Though, not even purely mathematical models would be totally immune to

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[9] Boehm [10] recommended a minimum of 5 records for local calibration of his COCOMO model. Ideally there should be more records.

subjectivity. Whatever technique is used some subjectivity is involved, either in making the estimates themselves or in calibrating some inputs into the model.

Although the core of this dissertation is focused on effort drivers and influence factors, it should be mentioned again that there are also some possible causes for too low nominal effort estimates, e.g. due to over-optimism when estimating effort or a price-to-win bid (see page 3). Apparently it is quite common that estimators often blur the distinction between price-to-win and realistic estimate. The resulting estimate is then becoming a mixture of both [69, 70].

In addition, in cases with too high effort estimates, the remaining effort could have been used to improve the delivered product (see Parkinson's law).

There are a number of critical success factors to cost estimation. In order for an estimate to be accepted and adhered to, it must involve all team members and in particular the project manager. In order for the project estimate to attain any degree of accuracy, it is important that the requirements are defined and documented prior to the production of an estimate. Additionally, some reserve built in for unanticipated problems can help to improve estimation success rates. Finally, the most critical success factor for engineering effort estimation is that experience and past project data should be documented utilising the presented activity based time recording method (see page 6) and used to aid the estimation of subsequent engineering projects.

5. Conclusions and recommendations

The main estimation techniques used across engineering design are analogy and expert estimation with varying degrees of formality and structure. This dissertation presented a new semi-parametric but practice-oriented approach for engineering design effort estimation in the industrial plant industry. In a general sense, this new engineering effort estimation procedure has been developed in the same way as similar parametric methods.

Much energy has been spent on definitions, rules and level of detail required for this procedure. Nevertheless, in the quest to obtain statistically significant findings, relevant factors may have been overlooked. Therefore, engineering effort estimation still presents many opportunities and challenges for researchers and practitioners alike.

5.1 Conclusions for development of scientific discipline

The development of an engineering cost estimation procedure using non-software metrics is a significant contribution to the field of parametric cost estimation. Researchers can build on this work to develop cost estimation methods in neighbouring engineering fields.

The problem with expert opinion based nominal effort estimation remains unsolved. It is not possible to compute nominal effort. Moreover, due to the notorious lack of analogous data a non parametric solution would be preferable.

The list of influence factors, their definitions, and their relationships provide useful insight for science and research. Results show that these influence factors are dependent on each other and that they are good indicators of engineering's complexity.

The consolidation of the estimation procedure brought about an overloading of some influence factors. This was caused by the merging of two or more factors into one because of multiple viewpoints for some factors. Possibly, these need to be simplified or changed into separate influence factors. This and other adaptations to the model are long term opportunities for future research.

Data from five similar engineering tasks have been used to calibrate the procedure, but more data from different organisations and also different engineering tasks would be useful in order to perform more tests of significance on all parameters.

5.2 Conclusions for practice

This dissertation is intended to assist experienced engineers in reducing the risk of inaccurate effort estimates. Practitioners will benefit because it is the first engineering effort estimation procedure that provides a guideline for the industrial plant industry. The list of significant cost drivers and influence factors can serve engineers and project managers as an inventory of probable risks. Controlling influence factors is a significant improvement in project management. This helps project managers to anticipate appropriate action to achieve minimal effort variance.

The research process has revealed a number of effort relationships accompanied by definitions that guide practitioners how these findings may relate to their organization. The comprehensive list of effort drivers and influence factors will help engineers to identify the relevant factors in order to take preventive action.

With the aim of being a useful tool for practitioners the procedure has been designed to be adaptable to other organisations or neighbouring industries. However, the initial calibration is representative for the surveyed organisation only. This is why the calibration process is part of the procedure. The procedure will be much more useful to individual organizations if it is calibrated for their use.

6. Summary

A new semi- parametric method to estimate engineering effort has been presented. The new procedure shares commonalities with existing approaches in adjacent software engineering disciplines.

The requirements for the new engineering cost estimation procedure have been defined. The new procedure has been developed to provide practice-oriented features. Among these is a well- defined and pragmatic procedure is provided.

The central proposition at the core of this research is that it is not possible to calculate the nominal engineering effort by use of a parametric equitation alone. Nevertheless, a semi-parametric method will help to adjust the nominal engineering effort to the project’s complexity and to the dynamics of the environment. The term semi-parametric implies that the equation will represent a function that is characteristic of effort drivers and stochastic influence factors.

The identification of stochastic influence factors and effort drivers is pivotal to this work. Influence factors and effort drivers were defined after extensively surveying recent engineering literature. Influence factors are stochastic while the effort drivers depend on complexity. Effort drivers will be used to adjust the nominal effort to an engineering task’s complexity while influence factors represent the dynamics of the environment.

The equitation to adjust nominal estimation to the dynamics and complexity of an engineering design task contains three different types of parameters: additive, multiplicative, and exponential. The nominal effort is additive. Influence factors are multiplicative because they all have global effects across the overall system. Influence factors are used to adjust to the dynamics of the environment. Effort drivers are exponential because they have both a global effect and an emergent effect for larger projects. Effort drivers are used to adjust to the complexity level of the requirements.

Five executed engineering design order examples have been scrutinized in the search for time consuming engineering activities and common problems. These data has been used to test and calibrate the new procedure.

Finally the theses have been validated. The usability of the new procedure has been proofed using the examples of the explorative research.

The contributions of this dissertation to science and practice can be found in the search of a more quantitative cost estimation framework and in advancing the state of practice in the assessment of engineering design effort.

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