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A COMPREHENSIVE EMPIRICAL APPROACH FOR DETERMINATION OF SUCCESS FACTORS OF PRODUCT DEVELOPMENT PROJECTS

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1. Introduction

Empirical Studies become increasingly involved in Engineering Design Research [Ahmed 2007]. Goal of such studies is to obtain a better understanding how and to what extend successful product design is influenced by certain factors. Many research activities about isolated factors of the product development process, such as the role of the individual designer [Frankenberger 1998], have taken place and lead to fruitful results. However, comprehensive or holistic [Schregenberger 1998] studies, where designers are viewed within their organizational context, are still rare. A comprehensive understanding of the product development process becomes increasingly important for Engineering Management, as it finds itself more and more embedded in global, complex corporate structures.
What complicates comprehensive studies for academia is that it requires cooperation with the industry, in order to get data that represents the “real world”. Getting sufficient data of an acceptable level of quality from companies, shows to be challenging for engineering design researchers [Blessing 2008]. In addition, a research approach with a sound methodological framework is inevitable in order to ensure that all factors that potentially have an impact on design success are considered and to handle the excessive amount of data required in a most efficient way. Although challenging, empirical design research studies appear to benefit from industrial involvement [Cantamessa 2001].
This paper proposes an approach for a comprehensive empirical Engineering Design Research study in the industry (called the Comprehensive Empirical Approach in the following). The approach provides a tool to support consideration of all the influencing factors - called ***Potential Success Factors*** in the following - on design success within the domain of interest, the Development Department. With help of quantitative analysis it will be tested if there are Potential Success Factors that contribute more to successful design - then considered as ***Success Factors*** - than others. The implementation of research results in the industry is an important aspect of this research effort, which is why the findings will be evaluated for their causality and usability for Engineering Management.
The Comprehensive Empirical Approach is currently applied on design projects that were performed in the industry. In order to utilize a sample size that allows the use of quantitative analysis methods, a significant amount of projects is investigated in this study. This allows to obtain results of generic rather than specific nature. The data is collected from archives where the development projects are documented but also through interviews with Project Leads and Engineering Managers.

2. Framework of the comprehensive empirical approach

The underlying idea behind the Comprehensive Empirical Approach is to describe the Product Development Process as a matter of cause and effect. The causes (x_i) are all of the factors that have an influence on the development process (Potential Success Factors), while the effect (Y) is the outcome of the process and unit of measurement, *Successful Product Design*. Figure 1 illustrates this relationship in an Ishikawa-Diagram. It happens, that all of the Potential Success Factors (x_i), which are found from literature research and interviews, fit in one of the six categories: Information, Environment, People, Method, Process and Management.

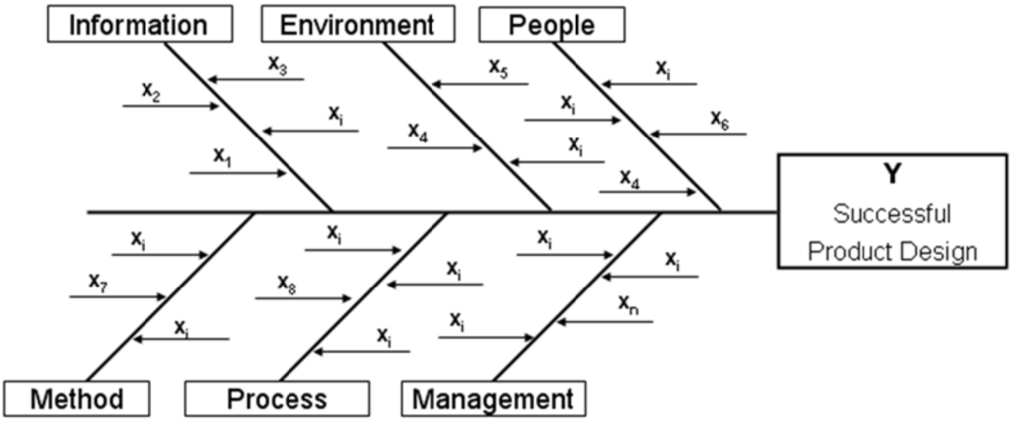

Figure 1. Development process as cause-effect relationship

If all the causes (x_i) as well as the effect (Y) can be quantified and if a statistically significant amount of data is collected from different development projects, a quantitative hypothesis check with statistical methods can be performed (Figure 2). Performing this check for each cause with the effect will show if there are Potential Success Factors that significantly contribute more to a successful design project (in that case identified as Success Factors) than others. If no significant factors are found, it will have to be assumed – as the opposite can not be proven – that all Potential Success Factors found in the literature are equally relevant to successful product design.

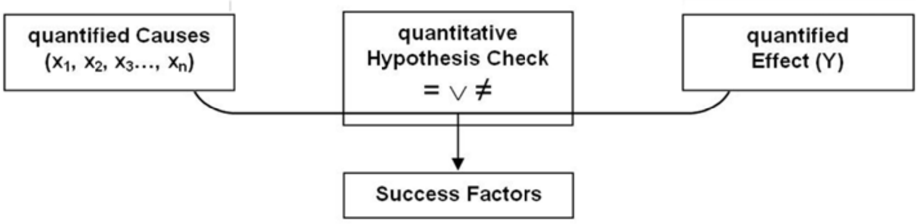

Figure 2. Hypothesis check to determine success factors from all potential success factors

2.1 Quantification of the effect

The quantification of the effect deals with the question of how to measure the success of product development projects. It is not possible to define *Design Success* in one measure. First of all, one has to decide on the domain of interest. The domain is a unit in the company which is evaluated using a specific success metric. For instance, the Marketing Department will have a different metric (e.g. customer requirement anticipation) than the Development Department (e.g. customer requirement fulfilment). Of course, all of the domain specific metrics contribute indirectly to profit, which is certainly the one measure organizations are most interested in. However, as this research effort aims to provide measures on how to improve the Product Development Process, it is important to be aware that the domain Development Department and its metric determine the way success will have to be measured. Furthermore, the success of a domain is typically defined by more than a one-dimensional measure, as can be found in studies about success measurement in innovation management [Griffith 1996]. For the domain of interest in engineering design research, which is the Development Department, the following three dimensions are typically the success measurements (metric) the domain is evaluated against within a company:

- Dimension 1: *Development of Products that fulfil defined Product Requirements*
- Dimension 2: *Meeting Development Timeline*
- Dimension 3: *Stay within Development Budget*

For an empirical study it has to be decided which of these three dimensions is of most interest and will serve as the primary dimension. Defining a primary dimension is inevitable, as pursuing all three dimensions in one study with one set of data will lead to one of the following two issues:

- In order to determine the factors that distinguish successful from less successful development projects, an equal amount of successful and less successful projects have to be considered. If only successful or only less successful projects are investigated, the findings cannot be seen as verified, as the opposite was not proven. Finding an equal amount of projects with respect to one dimension of interest is doable. However, finding a sample size of projects that includes an equal amount of successful and less successful projects in different dimensions is very unlikely. For instance, if 50 projects are chosen for an investigation where 25 are seen as successful and 25 as less successful with respect to the first dimension *Product Requirement Fulfilment*, then the data would be suitable and valid in terms of verifying what distinguishes successful from less successful design projects with respect to this dimension. Conversely, all 50 projects could be completed in time, providing only successful projects for the second dimension *Meeting Development* Timeline. Success Factors of this dimension could not be determined and verified with such a data set. However, the two remaining dimensions (especially the second *Meeting Development Timeline*) should still be quantified and tested for their relationship with the primary dimension. Otherwise, the question if any project can be accomplished successfully if there was just enough time spent and resources invested, remains open.
- The three dimensions are not necessarily on the effect-side, but can also switch to the cause-side. This is especially true for multi-component products that have development cycles of several years. For instance, development budgets in companies are typically determined and distributed on a yearly basis. A development project that is planned for several years can be impacted by funding cuts during that duration. In this case, the third dimension *Stay within Development Budget,* which was thus far considered to be an effect, would now become a cause that impacts the first two dimensions.

In order to obtain specific research results that are statistically valid, the domain and primary dimension of the domain of interest in the study need to be determined. The next step is the quantification of the primary dimension.

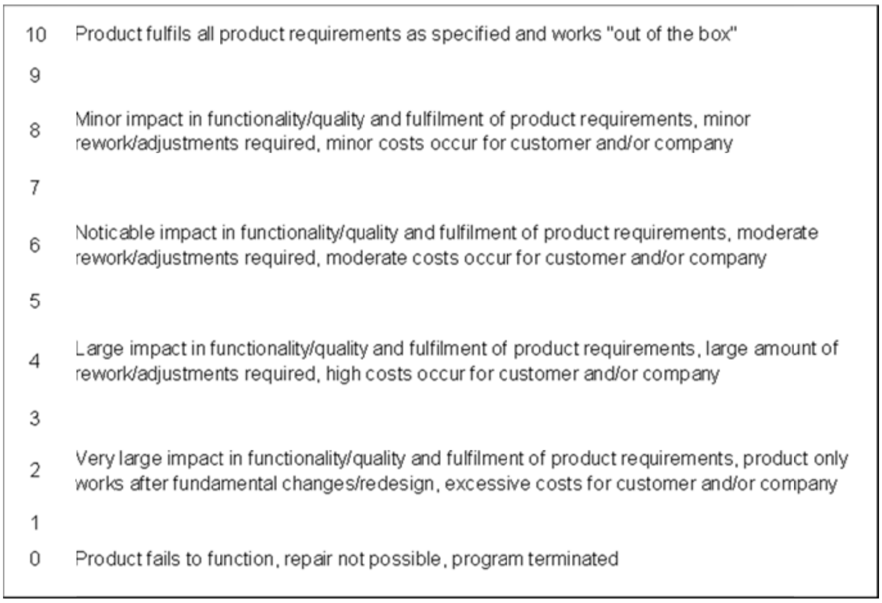

Figure 3. Example of quantified effect for an empirical study

As the process of an empirical design study requires the conversion of primarily qualitative data into quantitative data, two data types are of use: nominal or ordinal. When quantifying originally qualitative data, it is important to define points on a data scale using a clear description. This will help the researcher and third parties (for instance if data is acquired via interview) better understand the reasons behind the decision, making a rational judgement rather than an unspecified rating anywhere on the scale. Figure 3 shows an example of an ordinal success quantification scale how it could look for an empirical research on development projects of mechanical engineering products.

The dimension of interest in this example is *Product Requirement Fulfilment*. The scale with definitions on every second scale point, helps to make the study independent from a specific source of data. When choosing the projects to be investigated for such a study, we must ensure that enough projects are available for the whole scale of low to high scores. A statistically valid conclusion cannot be derived if the sample set of projects is only on the high (successful projects) or only on the low end of the scale (less successful projects). The quantification of the effect is done independently from any cause. This, together with the clear definition of the scale, should allow for collection of data with a high degree of objectivity.

2.2 Quantification of the causes

The causes that subsequently lead to the effect in product development sum up to an extensive amount of data. A comprehensive literature research on what are Potential Success Factors for of engineering development projects lead to an Ishikawa-Diagram, consisting of a total of 63 causes (x_n) in the six categories, for the domain Development Department. The Comprehensive Empirical Approach demands a quantification of all the causes in order to perform a hypotheses check against the effect. If a sample size of 50 projects (N) is considered for a study – which is a reasonable size to expect statistically valid results – the total amount of data points that have to be collected will be: $(x_n + Y) \times N = (63 + 1) \times 50 = 3200$. This number shows why comprehensive studies are so difficult and rarely conducted. We propose a systematic method of reducing the data size on the cause-side to a manageable figure without sacrifying comprehensiveness of the approach. This simplification is based on the following two considerations:

- The results of the empiric study are intended to be of practical use for Development Project Leads and Engineering Managers working in the industry. Keeping this in mind, the data set can be reduced to the Potential Success Factors that can be controlled or at least influenced by these parties, i.e. *Team Size* or *Team Composition*. Team Leads will certainly be interested in results that suggest measures how to form productive teams. Conversely, certain Potential Success Factors, for instance, *Creativity* – which can be found in literature frequently – are difficult to be controlled or influenced by an Engineering Manager or Project Lead when setting up a Development Project. In addition, it has to be verified whether there is a way to quantitatively measure such a cause. In psychology, there is no common understanding or way of measuring *Creativity*. While it is commonly acknowledged as a personal trait, there are researchers that consider it as result of situational circumstances and the environment [Amabile 1996]. Therefore, the first reduction in the data sets relates to the practicality of the research results on the Potential Success Factors in the six categories. The reduction needs to be made with respect to the dimension of interest in the specific study.
- Use of an iterative rather than a direct approach to determine Success Factors. Instead of quantifying each cause, it is possible to combine certain causes into groups, which are then quantified as one measure. This can be done by elaborating an Affinity Diagram. The idea of the Affinity Diagram is to group individual objects that share certain attributes into a higher level category. For instance, in literature, aspects of performing Conceptual Design are oftentimes mentioned as factors leading to design success, such as: *breaking problems into sub-functions*, *use of creativity techniques for solution finding*, *finding of many alternative solutions, rough analysis in early stages, etc.* A higher level category or cause, where all these single causes fit, can be found in *Conceptual Design Performed.* By defining one quantitative scale with respective definitions for this higher level cause, it is possible to evaluate in the hypothesis check if and to what extend the cause *Conceptual Design Performed* has

contributed to successful product design. If this higher level cause is found to have an impact, a subsequent study can be performed to determine which exact aspect of *Conceptual Design Performed* had the most impact on the effect.

Figure 4 shows the reduced Ishikawa Diagram of originally 63 causes after applying the two criteria to reduce the amount of data on the cause side. The first criterion of practicality led to a reduction of causes from 63 to 47. Finding higher level causes for these with help of the Affinity Diagram reduced the causes to be collected and quantified to 18, as they are shown in Figure 4.

For 50 projects now only $(x_n + Y) \times N = (18+1) \times 50 = 950$ data points have to be considered compared to 3200 originally.

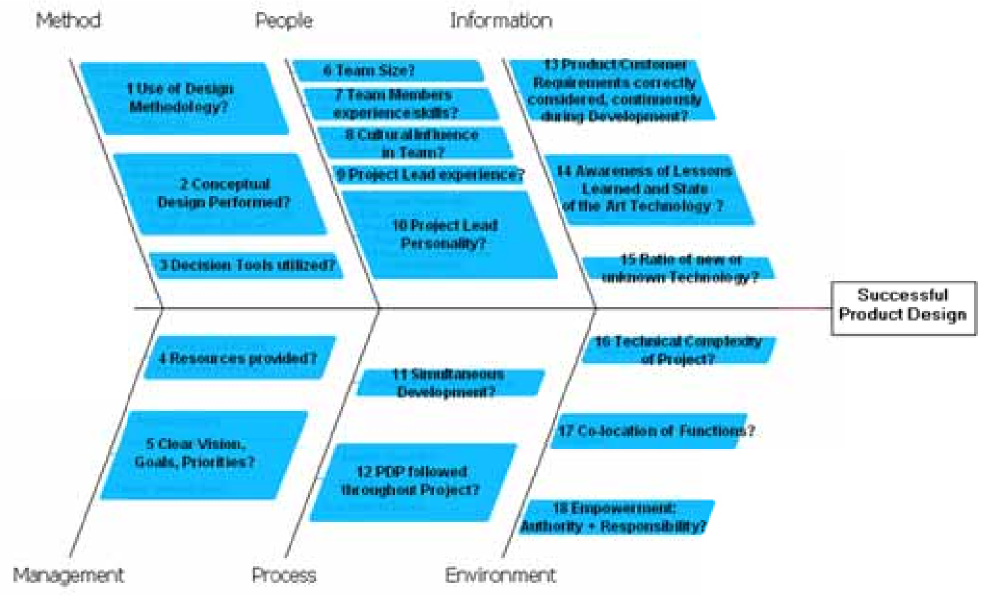

Figure 4. Higher level causes as measures to reduce the amount of input data

The use of an iterative approach with higher level causes does not necessarily lead to final results, which are causal Success Factors – this would only be the case for causes that were not able to be grouped with other causes into a high level cause. However, it still provides a good way to reduce the amount of data required on the cause side, as can be seen in Figure 5.

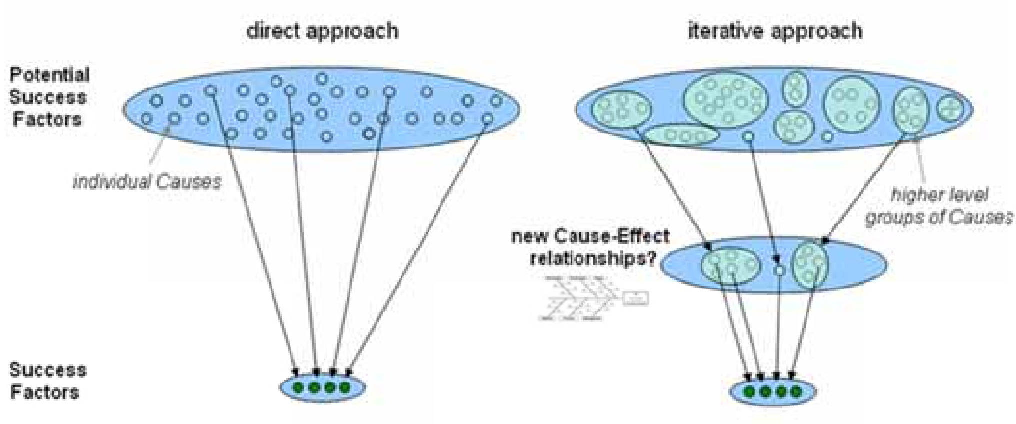

Figure 5. Reduction of required data sets through iterative approach

The higher level groups of causes found of importance in the first iteration will have to be investigated in detail in the next step. Again, special attention has to be given to the cause-effect relationships, as these could change with the next iteration. Figure 5 illustrates how the iterative approach differs from the direct approach. An additional advantage of the iterative approach is that it allows the substantial research effort of a comprehensive empirical study to be split into smaller parts. For instance, a timely limited research program or PhD dissertation can be set-up to focus only on the first iteration, while following programs will then investigate the second or, if necessary, a third iteration level.

2.3 Data analysis and verification

After the effect and the causes – or higher level groups of causes – are quantified for a stastically valid amount of projects, a hypotheses check can be performed between the effect and each cause. Statistics software will be used for this data evaluation. This will not only allow proper graphical illustration, but will also allow verification by determining the inherent level of confidence the results have. Suitable methods for evaluating the two independent variables (cause and effect) against each other are, for instance: regression or box plot.

The outcome of a study where qualitative data is transferred into quantitative (nominal or ordinal) and then evaluated is, in the end, of qualitative nature. Even though the results will be represented by numerical values, they cannot be seen as absolute. Instead, they must be used to discover relationship trends. For this reason it is important to know how confident the results are. We must not only rely on mean values, but the deviation of all data sets from these means needs to be known as well. For this purpose a statistical representation of results – allowing to verify the confidence of the data – is essential. Figure 6 shows an example of how such a result could look represented in a box plot. What is shown here is a hypotheses check of the effect *Product Requirements Fulfilled* against the cause *Technical Complexity of Product,* measured on a scale of 1-5. The results on the left side show a random distribution of data for 50 projects. This graph would suggest that there is no recognizable relationship. Not only do the means show no trend, the large size of some of the boxes reveals high deviations, which indicate that even the mean values are of low confidence level. The graph on the right side would suggest that a relationship between complexity and design success exists. Not only do the mean values show this trend, but the smaller boxes indicate a higher level of confidence in the data.

Once the causes have been determined as showing a trend that suggests that there is a relationship between the cause and the effect, the question needs to be asked whether this Success Factor is causal. To make this decision, it is useful to ask whether the Success Factor found is controllable or influenceable by Project Leads or Engineering Managers. If the answer is "yes", it can be seen as causal. If the answer is "no", one has to consider the cause found as an effect and think about controllable causes that lead to this effect. This can potentially result in a new study. The example of the hypothesis check shown in Figure 6 would be such a case. If the relationship turns out to be true (graph on the right side), *Technical Complexity* cannot be seen as a causal Success Factor. An Engineering Manager is not able to control this parameter. A company will certainly not decide to only focus on product developments with low complexity in the future, just because the success rate seems to be higher. Turning *Technical Complexity* into the effect and searching for causes for this effect could now lead to new causes, such as: *project planning quality* or *risk assessment during development.* These are causal Success Factors which allow for practical measures. They can directly be controlled and influenced by Engineering Management.

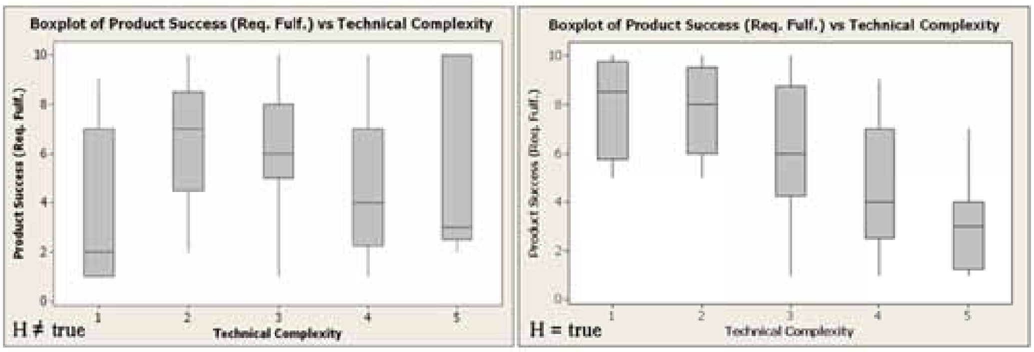

Figure 6. Example of false vs. true hypothesis

Figure 7 shows a process map of the Comprehensive Empirical Approach proposed in this paper. Following these steps will lead to results that derive from a comprehensive study of all of the Potential Success Factors. It is important that the researcher using this approach develops a mindset of continuously thinking in terms of cause and effect. As shown above, effects can turn into causes during the study. Having this in mind and asking the question of whether the results found are causal or not, should lead to an outcome of high validity and usefulness for engineering companies.

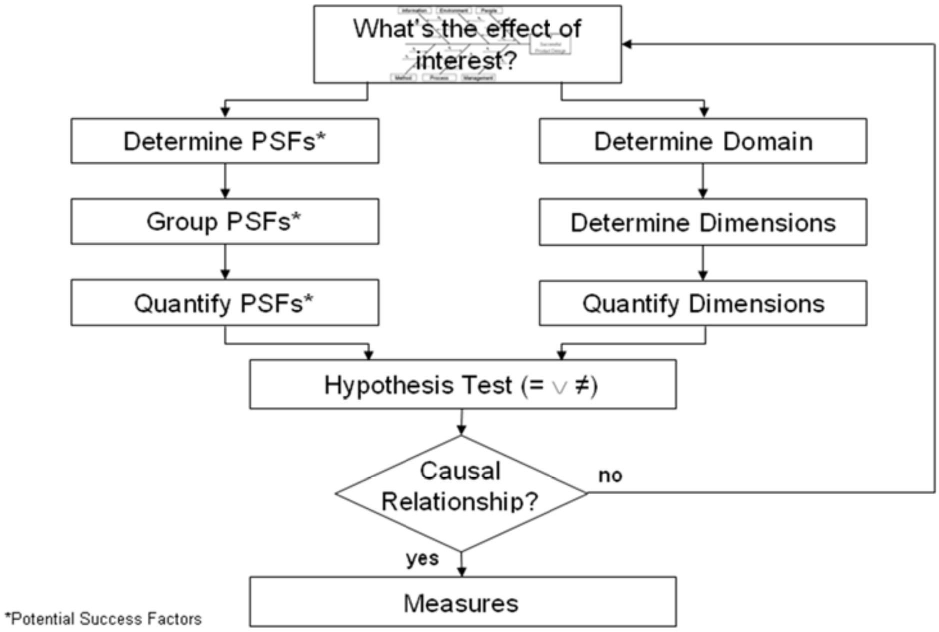

Figure 7. Process map of the comprehensive empirical approach

3. Summary

Empirical Engineering Design Research studies are essential in better understanding which factors contribute to successful product design. As designers and engineering managers find themselves in an increasingly complex organizational environment, it is important that comprehensive empirical studies are conducted which take all the influencing factors on design success into account. Such studies require cooperation of academia with the industry which bears certain challenges, such as the amount and quality of data which is accessible. The seek for comprehensiveness calls for a research approach with a sound methodological framework, supporting the researcher in identifying all Potential Success Factors and in handling the excessive amount of data required in a most efficient way. The Comprehensive Empirical Approach introduced in this paper suggests considering the Product Development Process as a matter of cause and effect. By quantifying all causes and the effect (Successful Product Design) and performing a hypothesis check, it should be possible to detect trends on which of all the Potential Success Factors contribute to successful product design more than others and are hence Success Factors. Causality and the usefulness of the results for the domain Development Department are seen to be linked. Success Factors which are determined and fulfil the causality criterion described should automatically allow for practical measures in Engineering Management.

4. Outlook

This paper proposes a new methodology for a comprehensive empirical evaluation of engineering design projects. The methodology is currently being applied to a set of approximately 50 industry projects. The projects investigated are development projects in an international company that develops and manufactures power generation equipment. A pilot study with a few projects is run to verify that the causes with their quantification scales allow for proper data collection. Depending on the causes found to show a relationship to successful product design – if any are found – it can then be verified if these are of company specific or general nature. The results will be presented subsequently.

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