Empirical studies into the dynamics of product development tasks

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Empirical studies into the Dynamics of Product Development Tasks

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Abstract

We investigated the causes of lateness of new product development projects in a lithographical equipment manufacturing plant. New product development projects consist of sets of work packages and we conducted our investigations at the work package level. We present and discuss empirical data regarding work package lead times, work package processing times, capacity allocation, project variability, and the opinions of engineers and project leaders about possible causes of project lateness. Our data suggest the existence of two types of uncertainty resulting in possible lateness. The first type is the normal uncertainty in project task duration, which can be modelled with a unimodal probability density function of task processing time. The second type of uncertainty can be modelled as the probability that the executor of a task is stalled for some time because of unexpected technological difficulties or changes in the product specification.

Empirical Studies into the Dynamics of Product Development Tasks

1. Introduction

Companies face substantial challenges in managing product development projects (Brown and Eisenhardt, 1995). Over the last decade much research has been published on new product development (NPD) projects. This is not surprising given the increased importance of product development or innovation for company success. Successful product development requires attaining goals with respect to product quality, development schedule, and development costs (Sheremata, 2000; Icmeli-Tukel and Rom, 2001). Product development is especially difficult when companies have little or no experience with the product and the process technologies employed in the product development project (Gupta and Wilemon, 1990). The use of new technologies can lead to undesirable project outcomes such as late time-to-market and/or low product quality and functionality. Despite these difficulties some companies deliberately choose to employ technologies that are new to them to develop products with high market distinction and to advance the company's technological competencies (Tatikonda and Rosenthal, 2000).

Considering the potential risks of product development, effective management of product development projects is of great importance. Project planning depends on the knowledge available in the organization regarding the tasks to be performed, the relationships between these tasks, and the time needed to complete a task. If all these elements were known with certainty, the project could be completely planned in advance, and then executed according to plan, resulting in the planned output at the planned time. Development projects, however, are not deterministic; the design tasks to be executed are generally not fully known in advance, nor are the exact relationships between the design tasks and the amount of time needed for a design task. As a result, control of a NPD project is an on-line process that responds to new information regarding the design tasks, their relationships, and the time needed.

In this paper we investigate the uncertainty that is encountered in the planning and control of NPD projects in a lithographical equipment manufacturing plant. We performed a literature review to identify the main characteristics of NPD projects and the different types of uncertainty. Based on this review we chose the work packages (or design tasks) allocated to engineers as the unit of analysis in this research. Next, we empirically investigated different types of uncertainty in a series of measurements. In an initial study, we started by measuring the difference between estimated work package lead times and actual work package lead times in an electronic product development project. In follow-up studies we researched underlying sources of uncertainty. We looked into the difference between estimated and actual processing times of work packages, the fraction of time that engineers allocate to work packages as a function of the nearness of the work package due dates, and the changes in the set of work packages in three development projects as these projects evolved over time. Finally, we performed a qualitative study of the opinions of engineers and project managers about possible causes of project lateness. Relating all these data provides information about sources of uncertainty in NPD projects and provides us with ideas how an organization may deal with these disturbances.

Before we present our empirical data we will first identify causes of uncertainty in NPD projects as mentioned in the literature.

2. Product development projects

Brown and Eisenhardt (1995) give a thorough review of the product development literature. They distinguish three main research streams: the rational plan research stream, focusing on the determinants of financial performance of a new product; the communication web research stream, focusing on the effects of communication on project performance; and the disciplined problem solving research stream, focusing on the effects of the development team, its suppliers, and the leaders on the actual process of the product development project. We position this paper in the disciplined problem solving research stream, as we study elements of the product development project.

There seems to be wide agreement that the amount of uncertainty is an important characteristic to distinguish between different types of product development projects. Product development projects with low technological novelty (i.e. low uncertainty) and low complexity are denoted as incremental innovations or as derivative or support projects. Product development projects with high technological novelty (i.e. high uncertainty) and high complexity are denoted as radical innovation or as platform and breakthrough projects. (Wheelwright and Clark, 1992)

The amount of uncertainty in a product development project has implications for the way in which the project may be planned and controlled. Project planning refers to the identification of the tasks to be done in order to realize the functional specifications, to the allocation of resources to the tasks in the project, and to the setting of due dates for the completion of the project. The work to be done can be broken down into work packages; a work package being a set of development tasks required to determine values for a given set of design parameters such that a given subset of functional specifications is realized. The set of all work packages together with the precedence relationships between work packages constitute the project network at a specific point in time.

In a low-uncertainty product development project, the project will consist of a stable network of work packages with low uncertainty in time and resource requirements per work package (see e.g. Wheelwright and Clark, 1992). Conventional project scheduling techniques, such as CPM and PERT, are readily applicable here (see e.g. Meredith and Mantel, 1989; Ulusoy and Özdamar, 1995). A high-uncertainty product development project, however, can be expected to be different in this respect. At the start of the development project, a set of work packages can be defined based on the existing product specifications. For high-uncertainty NPD projects Khurana and Rosenthal (1997) recommend managing the risk with thorough contingency planning, generating multiple product concepts, developing alternative solutions in parallel, or even creating competing design teams for products or subsystems. During the execution of the project, engineers are likely to discover new problems or opportunities, are faced with new problems or opportunities that result from cross-functional problem solving and conflict resolution, and are confronted with changes in the product specifications. These events all can result in new work packages that were not foreseen at the start of the project, or in work packages requiring much more capacity than initially estimated.

Project planning anticipates on the activities to be performed in a project, in particular on the duration of the activities (work packages) in the project. Much attention has been paid, both in the professional and scientific literature, to the estimation of the duration of activities of a network. Projects with uncertain activity duration are modelled as PERT networks. Many different distribution functions have been suggested for modelling the duration of uncertain activities, such as the exponential, the Gamma, the Beta, and the triangular distribution (Traveres, 1999). Bowers (1994) discusses the relevance of using a particular type of distribution function and proposes a method to systematically combine the experience-based knowledge about project activity duration that is available in the project team, in the company, and in the external world. He proposes to use triangular distribution functions, because these are easy to interpret by management, and suggests classifying design activities according to uncertainty, measured by the ratio of the estimated and actual duration. In the example given in this paper, activities refer to aggregate tasks such as engine design or frame design, carried out by teams of engineers. Williams (1995) discusses the nature of duration estimates in PERT networks, in particular the impact the estimated value may have on the execution of the activity. He states that 'a natural consequence of the idea of the PERT estimate as a target is the observation that the actual duration is rarely less than the target', the main cause being the well-known Parkinson's effect, (Parkinson, 1957), implying that people tend to slow down speed of work if progress is relatively high, and vice versa. The result of this behavioural effect is that the probability density function of the activity duration will have a higher probability for the central estimate, and a lower standard deviation, than it would have had otherwise.

Thus uncertainty in NPD projects may come from different sources and complex interactions may exist between the planning, execution, and control of NPD projects. In the initial planning, product specifications may be vague and work packages for alternative solutions may be incorporated in the plan. During execution, product specifications may be adapted and solution options may be dropped. All these uncertainties and changes have an effect on the work packages assigned for execution to the engineers, and have an impact on the predictability of work package completion time. Moreover, at the execution level, engineers may respond to targets and to progress, both in a negative and in a positive way; project control must anticipate this behaviour. In this paper we report on a number of quantitative studies into planning and execution of work packages of a new platform development project in a high-tech capital equipment-manufacturing company. To our knowledge no research has yet been reported in literature that deals with NPD projects at this level of detail (the work package level).

3. Research Approach

Empirical data on the execution of NPD projects at the work package level are difficult to obtain. It requires that the researcher gets access to the product development department and earns trust from the project management and the engineers. Moreover, data need to be collected over a considerable period of time. This requires the researcher to be "part" of the organization. As a result, simultaneous collection of this type of data from various companies is very difficult. Therefore we have developed a close working relationship with one company only, and collected data during a number of years. We are aware that the data collected are company-specific and that the observations based on these data may be contingent on the characteristics of the company. In section 4 we therefore give a short description of the company and its working methods. Details on working procedures relevant for the interpretation of the collected data are also given in section 6, where the additional studies are described.

4. Description of the company

The Company

The studies were conducted during the years 1998-2001 in a company that develops, produces, and services advanced micro-lithography systems that are used for the production of IC's all over the world. In the year 2000 the company realized net sales of 2,184 million Euros, orders for 464 systems were received, and 368 systems were shipped. At the end of the year 2000 total installed base was over 1,500 systems. The product development projects of the company are time-paced with a one-year new product release clock speed. Historically, accelerations in technology development and in market demands transformed this company in a very short time span from a rather small one-product-one-project organization into a highly complex multi-products-multi-project organization. In the year 2000 the company employed 4,377 people, of which over 1,000 engineers. Apart from final assembly and testing, all manufacturing activities were subcontracted.

Development organization

The development department is functionally organized with engineers temporarily assigned to development teams on a project basis. This type of organization guarantees that the knowledge of engineers keeps pace with the general level of knowledge available in their functional domain in the organization, while still being fully committed to applying this knowledge in the development project that they are working on (see Allen et al., 1988). Project teams are formed at the start of each new development project, and project managers compete for the capacity of the different functional engineering departments. The company has multiple development projects on hand simultaneously, some of which are radical or new platform projects.

Project planning and control

At the beginning of a new product development project, the product specifications are not yet definite and clear. The philosophy behind this way of working is saving time. According to the concurrent engineering approach, project duration can be shortened by performing processes that used to be sequential in parallel or concurrently (Clark and Wheelwright, 1993; Smith and Reinertsen, 1995; Prasad, 1996; Krishnan et al., 1997). This implies that before product specifications are completely defined, the development processes are allowed to start. The projects are planned and controlled with MS Project software. Project leaders use Gantt charts and CPM networks for project planning. The project team identifies the work packages that have to be performed in order to realize project objectives, and the project team determines the precedence relationships between work packages. Also the processing times of work packages are estimated. These are all 'most likely' estimates (according to the estimators), no explicit pessimistic and optimistic estimates are given, as is required by, for example, PERT (see for instance Neumann and Steinhardt, 1979; Taylor and Moore, 1980). This information is used to calculate the planned finish date of the project (is it possible to realize the project due date?), to guide engineers in their work planning (when must a certain work package start and/or finish?) and as a standard to evaluate project progress. Project progress is discussed weekly with the project team. Therefore project plans may be subject to change each week. Also, when product specifications change, new work packages may emerge, or work packages that were planned may be deleted. Changes in product specifications also require updates of the project plan.

5. Initial study: estimated versus actual lead times

Critical to the controllability of the project is the extent to which engineers can reliably estimate when an allocated work package will be completed. We therefore started the research with collecting data on the accuracy of the work package lead time estimates (due date minus release date). Data were collected from ten engineers working on an electronic product development project. They were asked to make an estimate of the lead time of each work package allocated to them. Each engineer could work on two or three work packages simultaneously. An engineer estimates the lead time of a newly assigned work package by estimating how many hours of work will be needed for this work package and by estimating how many hours of work will still be needed for the work on hand. Subsequently, the engineer adds up these two estimates and divides the result by the estimated hours of capacity available per week. All engineers had at least one year experience in their work and they all held an academic degree in their discipline. The company did not give penalties or rewards when estimates turned out to be wrong or right. The engineers made estimates for the work packages that where assigned to them over a period of twenty weeks. After a work package was finished, the realized lead time was noted. In total, data on 424 work packages were collected with estimated lead times ranging from one to eight weeks. Work packages with equal estimated lead times are comparable in the sense that they represent situations where the engineer perceives the same total estimated workload due to the work packages on hand (including the new one). Comparison of the realized and estimated lead times per group of work packages with the same estimated lead times gives information about the impact of workload situations on lead time estimation accuracy. Figures 1a to 1h show the frequency diagrams of realized lead times per group of work packages with equal estimated lead times (ranging from one to eight weeks). Table 1 gives the numerical data.

[insert Figures 1a to 1h]

[insert Table I]

As a reference for interpreting the frequency diagrams, we calculated reference frequency functions of the realized lead times based on the (naive) assumption that the time needed to complete a work package with L weeks estimated lead time is equal to L times the time needed to complete a work package with a one-week estimated lead time. This assumption implies that the engineer's way of working and the number of disturbances encountered are not affected by workload or by due date nearness. We observed that the realized lead time data for an estimated lead time of one week can be fitted quite well with a gamma distribution with parameters α=1 and β=1. Our assumption implies that the realized time for work packages with an estimated lead time of L weeks can be fitted quite well with a gamma distribution with parameters α=L and β= 1. The resulting reference frequency functions have been added in the Figures 1a to 1h.

Comparing the realized lead time frequencies with the reference frequencies we can observe that:

- realized lead times shorter than the estimated lead times occur much less frequently than suggested by the reference functions,
- realized lead times that are exactly equal to the estimated lead time occur much more frequently than suggested by the reference functions,
- realized lead times that are much larger than the estimated lead times occur much more frequently than suggested by the reference functions.

The first two observations are in line with Parkinson's Law (people tend to use up the time allowed for completing a task), and also confirm Williams finding regarding the relatively high probability of achieving the central estimate (Williams, 1995). The third observation, however, deviates from the earlier findings of Williams, who found that realized durations larger than the central estimate were underrepresented.

In an investigation of an aircraft development project, Bowers (1994) found that - for aggregate design activities – the standard deviation of the ratio of estimated to realized duration was about 0.3, which he rated as medium uncertainty. The last two columns in Table I show the mean and standard deviation of the ratio of estimated to realized duration. As the standard deviations of these ratios are between 0.2 and 0.45, these work packages may be rated as medium uncertainty (Bowers, 1994). Furthermore, the data in Table I suggest that the mean realized lead time is about two weeks larger than estimated, and that the standard deviation of the realized lead time is about three weeks, irrespective of the estimated lead time. A closer look at the data in the Figures 1a to 1h reveals that the average two-week lateness and the three-week standard deviation of the work packages are mainly caused by relatively few work packages that are extremely late. This suggests the existence of a source of lateness that occurs infrequently and that, when it occurs, causes the work package to be very late. Apparently this source of lateness is beyond control of the engineers, who otherwise seem to be able to manage their activities such that most work packages are completed close to their due dates.

6. Follow-up studies

To get a deeper insight into the underlying mechanisms leading to lead time inaccuracy we performed four additional studies. Firstly we investigated to what extent engineers can estimate the processing time of an individual work package; secondly we investigated to what extent engineers allocate capacity to work packages according to plan, and thirdly we investigated to what extent work packages are added to or deleted from the project during the execution of the project. To investigate these issues we collected quantitative data from nineteen engineers working on work packages belonging to two different software development projects, during a period of 42 weeks. This was complemented by a qualitative study concerning the opinions of engineers and project leaders on the reasons of project lateness. Before giving the results, we will first give a description of the software projects and the methods of data collection.

The software development projects

The two development projects are part of a larger project for developing a new micro-lithography system. The projects both consist of software development activities. The reason for choosing these two projects for our study is twofold. First, software development is an environment in which engineers and project leaders are accustomed to making detailed project plans, so collecting detailed project data for our empirical study would not disturb their normal planning activities. Secondly, in this organization software projects (in the realization phase) are considered to be the least uncertain with respect to work package structure and lead times. The two projects started in the fall of 1997, the collection of data started in July 1999 and finished in May 2000. Since our study did not start before July 1999, we could not collect any project data in the period before July 1999. The two software projects are called basic software and application software, and are part of the larger Software Layout development project.

The software projects are planned and controlled as follows. Functional specifications of the software project are translated into work packages. Precedence relationships between work packages are defined and work packages are allocated to engineers. Engineers estimate processing times of work packages and discuss their estimates with the project leader. Based on these estimates, the project leader develops a project plan and allocates work packages with a planned finish date to engineers. Because of the difficulty in estimating the processing times accurately, the estimates are updated every week. During project execution new problems may be discovered that require the definition of new work packages. Then these new work packages are added to the work package structure and the project plan is updated. Furthermore, it can also occur that a work package is removed from the project plan because it has become redundant. Project leaders prevent engineers from "running idle" by allocating more work than can possibly be done in a certain period. The project leader also prevents engineers from overload by sometimes postponing the due dates of work packages. The workload of an engineer can also be controlled by adjusting the desired ambition levels of work packages.

Data collection method

We collected information on the two software projects at the beginning of each week. The engineers and the project leader provided this information for each project. Eight basic software engineers and eleven application software engineers estimated the required processing time of each of their work packages as soon as the work package was known or planned. Each week engineers filled in an electronic time sheet to report how much time they had worked on each work package and how much time they thought was still required to finish the work package. Table II gives an example of such a time sheet.

[insert Table II]

Work packages are given a unique identification number (UID, see column 1 in Table II). After the engineers have been allocated work packages, they can fill in their first time sheet. They estimate the number of hours required for finishing each work package (initial estimate). In the 'Done' column they can fill in the number of hours they have spent on the work package in a particular period (week). The 'To do' column shows the estimate of the remaining workload of the work package. When this estimate is added to the number in the 'Done' column, a new estimate of the processing time is generated. For example, work package 456 has an initial estimated processing time of 10 hours, but in period 1999-40 the estimated processing time is 11 hours (1+10). When 'To do' is equal to 0, the work package is finished. The actual processing time can be calculated by adding up the hours an engineer spent on the work package in each period. The time sheets of engineers are passed on to the project leader. Based on the information of the time sheets, the project leader may decide to change the project plan.

Estimated versus actual processing times

We collected data on estimated and realized processing times of 108 work packages started during the 42-week measurement period.

[insert Figure 2]

Figure 2 shows the plot of actual versus estimated processing times for the 108 work packages in the data set, with as a reference a line that represents a linear relationship between realized and estimated processing times. The plot suggests that for many of the work packages the realized processing time strongly deviates from the estimate. Estimation errors may be related to the magnitude of a work package. We therefore also calculated the estimation processing time ratio, defined as estimated processing time divided by realized processing time (Bowers, 1994). The standard deviation of these ratios is 2.52. This standard deviation reflects the uncertainty of these work packages, which according to Bowers can be classified as very high, and is characteristic of trials and not of design activities.

To obtain some more insight into the relationship between estimation error and realized processing time, we split up the data set into three equal sets of 36 observations each; a set with small size work packages, a set with medium size work packages and a set with large size work packages. Table III gives the mean and standard deviation of the estimated error for each of these sets.

[insert Table III]

The table reveals that for small work packages the mean and standard deviation in the estimation error are much smaller than for medium and large work packages. We may expect that project timeliness is most endangered by the extremely large estimation errors (which occur relatively infrequently). To estimate the impact of the extreme values on the standard deviation we selected the 10 work packages (about 10% of the whole set) with the largest deviations, deleted them from the data set, and recalculated the standard deviations. The results in Table IV show much smaller standard deviations for the medium and large work packages.

[insert Table IV]

This indicates that a possible reason for the few extremely large deviations observed in the previous study on lead times estimates might be that the engineer had one or more medium or large work packages on hand for which processing times sometimes were much larger than estimated. However, this is unlikely to be the only reason for extreme lead time deviations, as large deviations also occur for estimated lead times of one or two weeks; situations where the work an engineer has on hand will probably consist of one or more small work packages, the processing times of which can apparently be estimated with relative high accuracy.

Capacity allocation and due date nearness

An implicit assumption in the planning of the project and the work packages is that engineers take the due dates of the work packages on hand into account when deciding on which work packages to work. In particular it is assumed that engineers process the work packages in order of earliest due date. To examine the effect of work package due date nearness on the capacity allocated, from the data sets of the two software development projects we derived the weekly fraction of capacity spent on a work package and the time-to-due date of that work package. This was done for all the work packages on hand during the measurement period of 42 weeks, and resulted in 835 measurements. Each of these measurements is plotted in the diagram of Figure 3.

[insert Figure 3]

The plot clearly reveals that, on average, the fraction of capacity allocated to a work package increases as the work package due date comes nearer. An exponential relationship between time to due date, *TDD,* and percentage of time spent, *%TS,* fits the data quite well. This relationship can be expressed by: $\%TS = 0.4665 * e^{-0.0133TDD}$ (coefficient of determination, $R^2 = 0.461$). The nearness of the due date of a work package (a short time to due date) positively influences the amount of time an engineer will spend on this work package. Thus, engineers indeed seem to take due dates into account when planning their work. However, there is a high variance in allocated capacity and the plot also shows that even when due dates are very near, the fraction of capacity allocated to work packages varies a lot, so due date nearness is not the only determining factor. Other factors might be missing information from other engineers working on concurrent work packages, or the emergence of work packages with even higher priorities. Work packages with a high priority may emerge during the execution of a project when unexpected problems occur which can only be solved by changing the work package structure, or when new market information leads to a change in product specifications, with the same effect on the work package structure. This is the subject of the next study.

Stability of project networks

We investigated the stability of the project network of the two software development projects by measuring the number of work packages in the network at the start of the project, and the number of work packages added to and deleted from the network over the measurement period of 42 weeks. Measurement took place at three-week intervals. We were able to also collect these data form a mechanical development project that ran concurrently with the two software projects. This enabled us to check whether project network (in)stability is discipline-specific.

The results are given in Table V and Figure 4. These results show high network instability for all three projects.

[insert Table V]

[insert Figure 4]

The application software project started with 96 work packages, 83 work packages were added and 46 were deleted during the 42 week period. From the 133 work packages in the network at the end of week 42, only 50 were known at the start in week zero. The basic software project started with 54 work packages, 49 work packages were added and 14 deleted. From the 89 work packages in the network at the end of week 42, 40 work packages were known at the start in week zero. The mechanical development project started with 374 work packages, 76 were added and 163 work packages were deleted during a period of 30 weeks. From the 287 work packages in the network at the end of week 30, 198 work packages were known at the start in week zero.

These data reveal that in this company project networks are quite unstable and very frequently new work packages emerge that may disrupt the natural flow of work of the engineers and overrule the existing priorities. Project network instability therefore may be an important cause of the large work package lateness observed in the first study (besides the other important cause: work package processing times being sometimes much larger than estimated).

Perceived causes for not realizing project plans

We complemented the quantitative data studies with a qualitative study of the opinions of engineers and project leaders regarding the characteristics of development projects. In this study we let engineers and project leaders think about the nature of the product development projects they had been working on, and about the reasons for project plans not being realized. We used the Nominal Group Technique (NGT) to structure small group meetings consisting of five project leaders and seven engineers of different engineering disciplines (software, physics, mechanics, electronics). This group of people is a representative sample of the development department.

The NGT allows individual judgments to be effectively pooled and used in situations in which uncertainty or disagreement exists about the nature of a problem or possible solutions (Moore, 1987; Fox, 1988). NGT typically includes four steps:

1 silent generation of ideas in writing (in response to a stimulus question);
2 round-robin recording of ideas (on a flipchart, without discussion);
3 serial discussions of the listed ideas (to understand their meaning);
4 voting to determine the most important ideas.

We gave the participants only one stimulus question and in two three-hour meetings this question was discussed. The stimulus question was: 'why are product development project plans not realized? In the first meeting, the twelve participants were split up into four groups of three. Within each group the participants first generated their ideas silently and next they combined their ideas on a flipchart. At the end of the meeting each group presented one flipchart with their ideas, i.e. the causes of not realizing project plans. In the second meeting the participants were again split up, this time into groups of two (to obtain a different group composition) and they were asked to cluster the causes, if possible, and to choose the cluster (or clusters) they found the most important. These clusters should give us a better understanding of the characteristics of product development projects and the causes of project plans not being realized.

The participants made ten clusters of causes. In Appendix 1 the clusters with all causes are shown. Here we suffice by giving the cluster names and a short description. The number of times a cluster was chosen as 'most important' is shown between brackets.

A *optimistic estimates* (4): engineers explain that they plan too optimistically or that they go along with an unrealistic planning. In reality more time is needed than planned.
B *vague specification content* (3): the functional specifications are the input for product development projects, but because these are formulated vaguely, it is not exactly clear what has to be achieved.
C *balancing between projects* (2): projects are related to each other; if one project is late, the planning of another project is affected (input is not available, so a delay occurs).
D *varying specification content* (1): specifications that are vague to start with, must be changed to become clearer and more definite. When specifications become clearer, the content or the number of work packages may change, sometimes resulting in more work than expected.
E *specification procedure* (1): a clear procedure on how to define, review, and change specifications is lacking.
F *unplanned activities* (1): engineers are often disturbed in their work by questions from

colleagues, telephone calls, discussions, meetings, or coaching of new colleagues. These unplanned activities diminish the amount of time available for work packages.

G *quantity of non-human resources* (1): a shortage exists of testing machines or parts of machines on which engineers can test their developed solutions.

H *not working according to the project approach: planning and tracking* (0): because of the high workload, not enough time is spent on project planning, tracking (progress measurement), and replanning.

I *quantity of human resources* (0): engineers are not focused on one project but are assigned to more than one project; key team members leave projects too soon due to a shortage of engineers (overload, work pressure).

J *quality of human resources* (0): many new team members are inexperienced or do not yet have the right company-specific training.

The results of this qualitative study are in line with the results of the other studies described in this article. The most frequently mentioned cause was an optimistic estimate, which is in line with our observation that work package processing times are often underestimated and sometimes even very much underestimated. The items B and D refer to causes due to changes in the work package structure; vague and varying product specification content. The item C, balancing between projects, confirms our previous finding that work packages may be stalled because other work packages are late.

The data in this research provide evidence of the existence of sudden disruptions with large negative impacts on work package progress, which seems to be due to the high technological uncertainty and the uncertainty about product specifications that are characteristic of highly innovative NPD projects. This suggests that in the planning and control of highly innovative NPD projects two types of uncertainty must be taken into account. The first type is the normal uncertainty in project task duration, which can be modelled with a unimodal probability density function of task processing time. The second type of uncertainty can be modelled as the probability that the executor of a task is stalled for some time because of unexpected technological difficulties or changes in the product specifications.

7. Conclusions

In this paper we have presented the results of an empirical investigation of possible causes of lateness of product development projects in a lithographical equipment manufacturing company. This company applies concurrent engineering principles in the planning and control of its development projects, and operates under a policy of releasing new products to market at regular and short time intervals. In this research the unit of analysis has been the work package, a design task assigned to an individual engineer. Product development projects consist of networks of work packages.

The research consisted of studies of data collected from development projects and a study of perceptions of engineers and project leaders. The first data study revealed that in the project studied, the engineers were quite well able to realize the estimated lead times assigned to work packages for the majority of work packages, but for a small number of work packages estimated lead times were largely exceeded. This suggests the existence of specific sources of disturbance in progress. In follow-up studies we collected data from two software development projects to investigate possible disturbance sources. Data about the estimated and realized processing times of work packages revealed that for the majority of work packages engineers were quite well able to estimate the processing time with reasonable accuracy; however, for a small number of work packages large negative deviations occurred. Comparing the data for lead time accuracy and work package processing time accuracy revealed that also other sources for lead time must exist. An investigation of the planning behaviour of the engineers revealed that on average they tend to take work package due dates into account when planning their work. Finally, we analysed data on the evolution of the set of work packages in projects over time, and observed that during the execution of projects many new work packages were added to the project and many work packages were removed. This indicates instability of project networks, leading to stalling of progress of work packages on hand and changes in work package priorities. This might be the second cause of the occasionally large excesses of work package lead times over estimates. The results of the qualitative study of the opinions of engineers and project leaders largely confirm the causes suggested by the quantitative project data. The results of this study suggest the existence of two types of uncertainty in new platform NPD projects. The first type is the normal uncertainty in project task duration, which can be modelled with a unimodal probability density function of task processing time. The second type of uncertainty can be modelled as the probability that the executor of a task is stalled for some time because of unexpected technological difficulties or changes in the product specifications.

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Appendix 1. Clusters of causes for project lateness

The remarks the engineers and project leaders made, have not been adjusted and have been copied directly from the sheets used during the study. The number of times the cluster was chosen as 'most important' is given between brackets behind the cluster name.

A optimistic estimates (4)

- optimistic planning of the project leader and the project member
- planning too optimistically
- go along with an unrealistic planning
- unreliable delivery times

B vague specification content (3)

- unclear specifications
- quality of specifications not sufficient
- vague specifications

C balancing between projects (2)

- balancing between projects is wrong → one project is faster than another
- balancing between different disciplines is wrong (for example electronics vs. mechanics, tooling vs. design)
- communication between projects is not working: volume control and interface agreements
- planning of Electronics/Software/Architecture is not known
- planning of System Engineering is not known

D varying specification content (1)

- no constant butchanging specifications
- specifications change/exchange between projects
- specifications are not present at the start of the project
- new (derived) specifications come up during development and implementation
- no specification control

E specification procedure (1)

- underlying specifications are not achieved or cannot be tested
- old design problems bite back
- the company gives unclear specifications to third parties
- I accept unclear assignments!

F unplanned activities (1)

- many small disturbances (questions, telephone calls, coaching, etc.)

- focusing on immediate questions that were unforeseen
- moving to another building interrupts development
- escalation outside the project

G non-human resources (1)

- no test tooling
- availability of machines is too limited
- too little machine time

H not working according to the project approach: planning and tracking (0)

- too much operational work → not much time for project planning
- no tracking → in the next planning the same mistakes are made
- lacking of an integral project planning
- admitting too late that the planning will be exceeded
- planning of complementary projects is not known

I quantity of human resources (0)

- several projects with one person, pushing priorities aside
- unclear net availability, allocate resource claim, resources are shredded across projects
- claim and allocation procedure does not work: must be more stable
- resources disappear, do not come back or are taken back, key persons leave projects too soon
- aftermath of former projects
- sickness of key persons
- no or too little resources, uncertain resource allocation

J quality of human resources (0)

- education of people in the project
- training of elementary skills in own discipline
- quality of project members (junior members without coaching)
- too little transfer of knowledge
- resource to which the job is allocated appears not to be the right resource

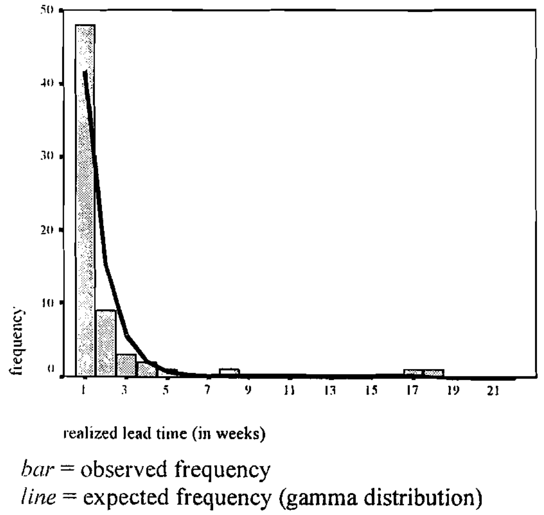

Figure 1a. Frequency diagram of realized lead times for work packages with an estimated lead time of one week (n=66).

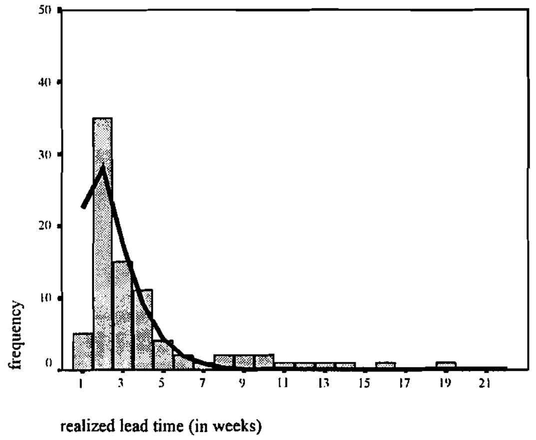

Figure 1b. Frequency diagram of realized lead times for work packages with an estimated lead time of two weeks (n=85).

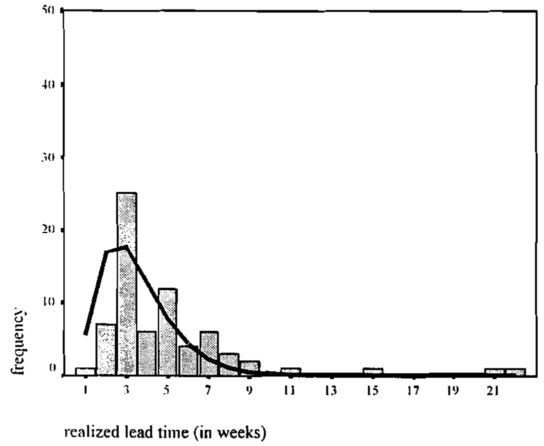

Figure 1c. Frequency diagram of realized lead times for work packages with an estimated lead time of three weeks (n=70).

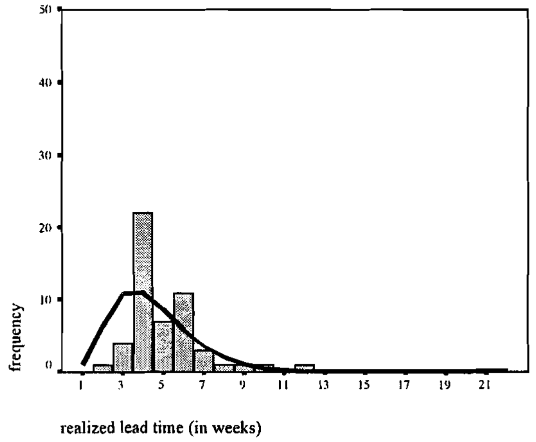

Figure 1d. Frequency diagram of realized lead times for work packages with an estimated lead time of four weeks (n=52).

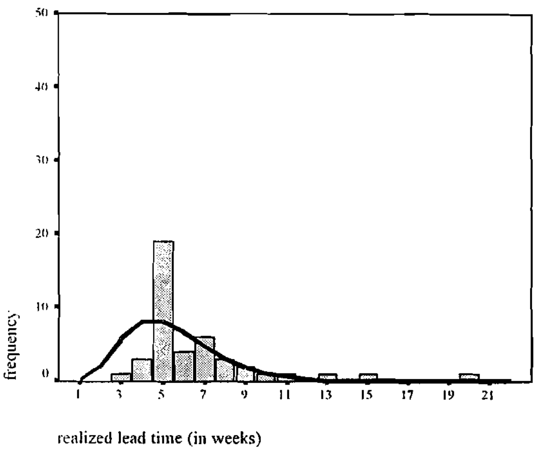

Figure 1e. Frequency diagram of realized lead times for work packages with an estimated lead time of five weeks (n=43).

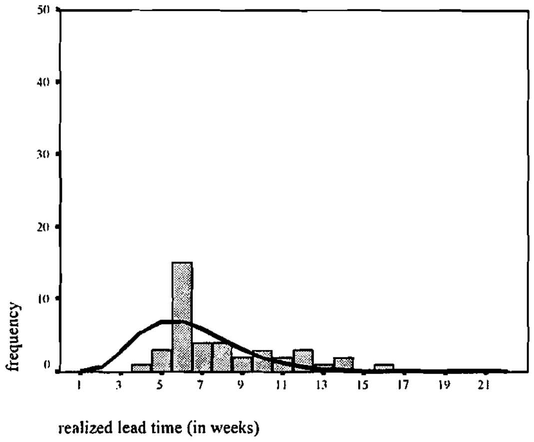

Figure 1f. Frequency diagram of realized lead times for work packages with an estimated lead time of six weeks (n=41).

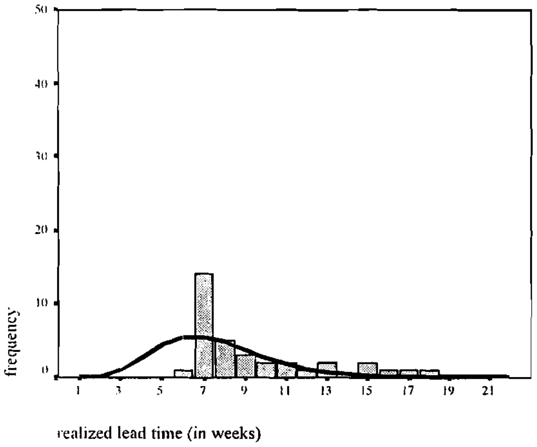

Figure 1g. Frequency diagram of realized lead times for work packages with an estimated lead time of seven weeks (n=35).

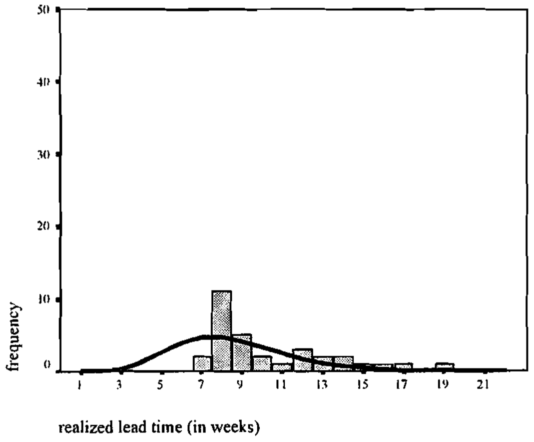

Figure 1h. Frequency diagram of realized lead times for work packages with an estimated lead time of eight weeks (n=32).

Figures 1a through 1h.

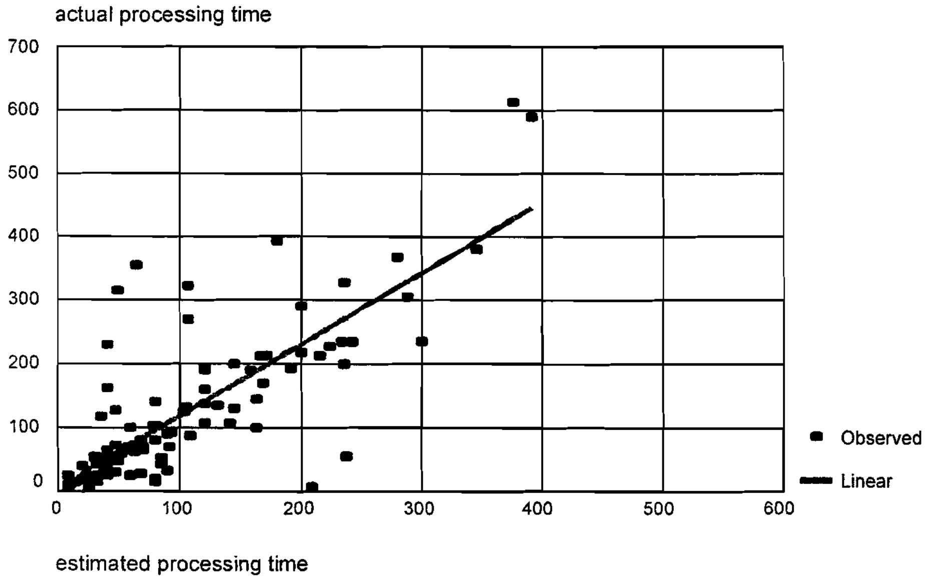

Figure 2. Comparison of estimated and actual processing time (in hours).

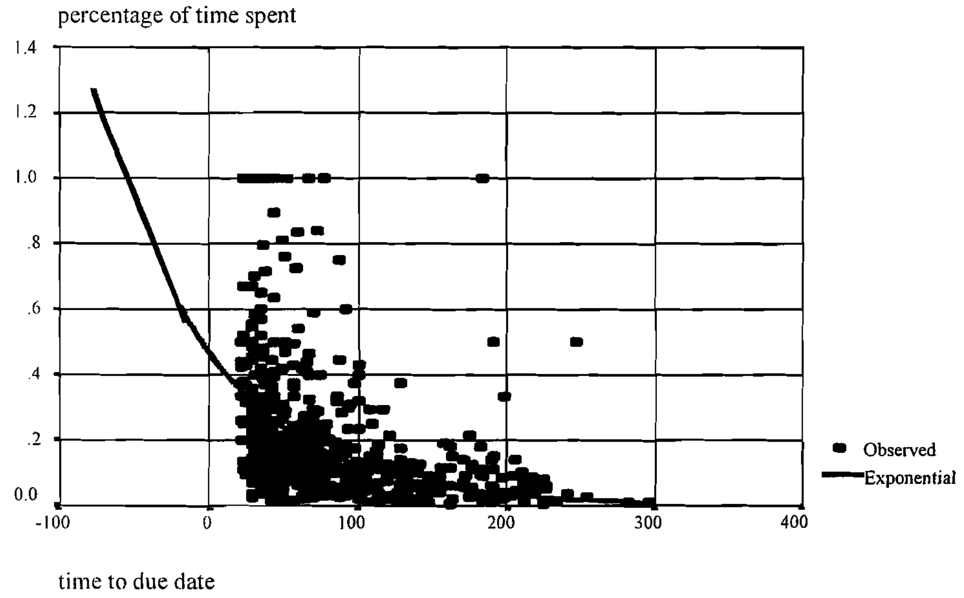

Figure 3. Comparison of time to due date (in days) and percentage of time spent.

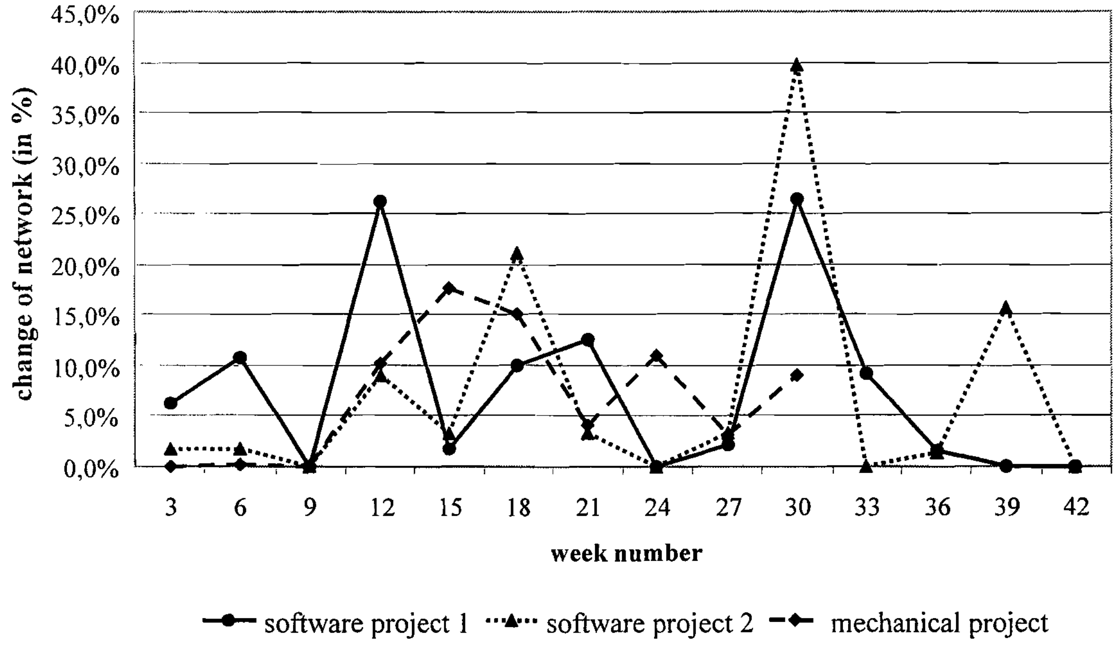

Figure 4. Changes (in %) of project networks of three different product development projects.

Table I: statistics of estimated and realized lead times (in weeks)

estimated lead time	n	mean realized lead time	min realized lead time	max realized lead time	mean lateness	standard deviation lateness	mean estimate/realized ratio	standard deviation estimate/realized ratio
1	66	1.98	1	18	0.98	3.00	0.82	0.30
2	85	4.02	1	19	2.02	3.52	0.77	0.43
3	70	5.01	1	22	2.01	3.72	0.82	0.44
4	52	5.06	2	12	1.06	1.82	0.88	0.28
5	43	6.67	3	20	1.67	3.18	0.86	0.27
6	41	8.10	4	16	2.10	2.95	0.83	0.26
7	35	9.49	6	18	2.49	3.34	0.81	0.22
8	32	10.47	7	19	2.47	3.18	0.82	0.21

Table II example of a time sheet (numbers are in hours)

Name:	**Engineer**		
Project:	**Application Software**		
Period:	**1999-40**		
UID	**Initial Estimate**	**Done**	**To do**
123	18	20	0
456	10	1	10
789	7	5	2

Table III estimated versus actual processing times of all work packages and of work packages divided in three groups (small, medium and large)

	All	**small ($8 \leq wp \leq 40$)**	**medium ($40 < wp \leq 105$)**	**large ($106 \leq wp \leq 392$)**
n	108	36	36	36
μ	-18.4074	-0.9167	-23.8056	-30.5000
s	72.2023	17.8027	79.1313	94.1471
Z	-2.6494	-0.3090	-1.8050	-1.9438

μ = the mean of $E_p - A_p$; s = standard deviation of $E_p - A_p$; Z = test statistic, $z_\alpha = z_{0.05} = -1.645$

Table IV estimated versus actual processing times of work packages excluding 10 work packages with largest deviations

	All	**small ($8 \leq wp \leq 40$)**	**medium ($40 < wp \leq 90$)**	**large ($91 \leq wp \leq 346$)**
n	98	33	33	32
μ	-3.2041	-0.0606	-0.0606	-9.6875
s	30.0532	18.3149	31.8551	36.9860

Table V: changes of project networks												
	Software project 1				**Software project 2**				**Mechanical project**			
Week	**new**	**del.**	**total**	**% change**	**new**	**del.**	**total**	**% change**	**new**	**del.**	**total**	**% change**
0	-	-	96	-	-	-	54	-	-	-	374	-
3	6	0	102	6,25%	1	0	55	1,85%	0	0	374	0,00%
6	4	7	99	10,78%	1	0	56	1,82%	0	1	373	0,27%
9	0	0	99	0,00%	0	0	56	0,00%	0	0	373	0,00%
12	23	3	119	26,26%	4	1	59	8,93%	6	32	347	10,19%
15	2	0	121	1,68%	0	2	57	3,39%	19	42	324	17,58%
18	9	3	127	9,92%	7	5	59	21,05%	33	16	341	15,12%
21	16	0	143	12,60%	2	0	61	3,39%	11	3	349	4,11%
24	0	0	143	0,00%	0	0	61	0,00%	1	37	313	10,89%
27	2	1	144	2,10%	2	0	63	3,28%	3	7	309	3,19%
30	18	20	142	26,39%	19	6	76	39,68%	3	25	287	9,06%
33	3	10	135	9,15%	0	0	76	0,00%				
36	0	2	133	1,48%	1	0	77	1,32%				
39	0	0	133	0,00%	12	0	89	15,58%				
42	0	0	133	0,00%	0	0	89	0,00%				
total	**83**	**46**			**49**	**14**			**76**	**163**		