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Managing the Process of Engineering Change Orders: The Case of the Climate Control System in Automobile Development

Christian Terwiesch and Christoph H. Loch

Engineering change orders (ECOs) are part of almost every development process, consuming a significant part of engineering capacity and contributing heavily to development and tool costs. Many companies use a support process to administer ECOs, which fundamentally determines ECO costs. This administrative process encompasses the emergence of a change (e.g., a problem or a market-driven feature change), the management approval of the change, up to the change's final implementation. Despite the tremendous time pressure in development projects in general and in the ECO process in particular, this process can consume several weeks, several months, and in extreme cases even over 1 year. Based on an in-depth case study of the climate control system development in a vehicle, we identify five key contributors to long ECO lead times: a complex approval process, snowballing changes, scarce capacity and congestion, setups and batching, and organizational issues. Based on the case observations, we outline a number of improvement strategies an organization can follow to reduce its ECO lead times. © 1999 Elsevier Science Inc.

"If we want to remain competitive in the future, we need to move from a company dedicated to developing excellent products to a company that achieves both, product AND process excellence." (SVP of development at a major automotive manufacturer)

Introduction

Engineering change orders (ECOs)—changes to parts, drawings, or software that have already been released—are part of almost every development process. They result from the fact that engineering is an iterative rather than a purely linear process and traditionally are targeted toward correcting mistakes, integrating components, or the fine tuning of a product [26,27,30]. ECOs are also an outcome of the growing level of parallelity in today's development processes, where information-absorbing downstream activities often are started prior to the completion of information-supplying upstream activities and thus have to rely initially on preliminary information [9,16,17,19,22,33].

The negative impact of ECOs has been reported in a number of studies. ECOs consume one-third to one-half of engineering capacity [28] and represent 20% to 50% of tool costs [20], which can easily account for over US$ 100 million in large development projects. However, the management of ECOs is not well understood despite this importance. In the past, both practitioners and researchers have tended to view ECO-related problems more as a tragedy than as a sign of

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process management. In particular, the support process administering ECOs has received little attention, although it has been identified as one of the root causes of ECO costs [7].

It is this ECO support process on which the present article focuses. It encompasses the emergence of a change (e.g., a problem or a market-driven feature change), the search for potential solutions, up to the final implementation of the ECO. Despite the tremendous time pressure in development projects in general and in the ECO process in particular, this process can consume several weeks, several months, and in extreme cases even over 1 year. Such delays create substantial costs confusion and sometimes even threaten the timely completion of the overall project.

In the case of the climate control system (CCS) development in a car, we show why a seemingly simple process of "just doing some small modifications in the product" can take so much longer than initially expected. We identify five factors that contribute to long processing times and outline a number of opportunities for improvement.

The remainder of this article is organized as follows. We first review the literature on the management of engineering changes and related topics in product development. After presenting our research questions and the methodology we have chosen to address these questions, we present the five main contributors to long ECO processing times that we have encountered. Based on our case observations, we outline a number of improvement strategies.

Background

ECOs are not always to the detriment of the project, as many cost savings or performance improvements are brought into the project in the form of ECOs. Thus, ECOs have a role in improving the product, and efforts to eliminate them entirely are both undesirable and unrealistic [7].

However, it is common that many and especially late ECOs are very costly to a development project. ECOs consume one-third to one-half of engineering capacity [28] and represent 20% to 50% of tool costs [20]. Clark and Fujimoto [7] as well as Lincke [20] report that 20% to 40% of die development costs in vehicle development are caused by ECOs.

Previous research has identified a number of strategies a development organization can adopt to reduce the negative consequences of ECOs. We classify this prior work into four groups and summarize the major findings in the form of "Four Principles of ECO Management," of which the first three are related to the technical problem solving characteristics of the change (and only briefly discussed here), and the last one is process driven and thus the subject of our further analysis.

Principle 1: Avoid Unnecessary Changes

New product development is an iterative process and thus will always experience some changes [26]. However, as Clark and Fujimoto [7] point out, many ECOs are not necessary changes and can be avoided if the engineer responsible spends more time on the first release of the component. Because, on average, every component has to be changed once [28], many engineers feel no reason to provide good information to other parties in their "first shot," as they know they will have to rework the component anyway. In addition, some ECOs look beneficial at first sight, but in the end provide only minor cost savings that do not justify the negative non-financial externalities caused by the change.

Principle 2: Reduce the Negative Impacts of an ECO

The second principle takes the occurrence of the ECO as given and focuses on minimizing the negative impact of the change. This impact is a function of the magnitude of the change [19], its timing [22], and the number of components [26] and tools [34] that are affected by the change.

Using the example of a dashboard, Krishnan [19] demonstrates how the magnitude of a change is driving the costs of implementing the change. Small changes can be implemented at low costs, whereas large changes can cause substantial time losses and high costs. Loch and Terwiesch [22] argue that not only the magnitude of an ECO but especially the time of its implementation drives the associated costs. Furthermore, if the component to be changed exhibits strong architectural couplings with other components, ECOs are likely to cause higher costs as, potentially, other components need to be modified as well [26]. The importance of product architecture and modularity have been discussed by Ulrich [35] as well as Gulati and Eppinger [14]. Finally, Thomke [34] suggests that the negative consequences on tools can be reduced through flexibility in the manufacturing process. An example of such flexibility can be found in the case of special materials for prototype dies (soft dies).

Principle 3: Detect ECOs Early

The third principle is based on the observation that ECOs become more expensive and harder to include the later they are implemented [23], thus making it desirable to detect all need for changes as early as possible in the process. This strategy of moving changes forward in time and thereby reducing their negative impact on other activities frequently is referred to as frontloading [11]. Recent advances in computer-aided design (CAD), rapid prototyping, and computer simulation have allowed development organizations to detect ECOs far earlier in the process, at substantially lower cost [11,32,34]. Frontloading also can be achieved by organizational means and formal design-for-manufacture methods, such as early reviews with manufacturing or logistics experts (for an overview, see [1,10]). This enables the organization to detect, at an early stage, changes that usually remain hidden until the corresponding downstream activity starts working.

Principle 4: Speed Up the ECO Process

The first three principles all have their roots in the engineering domain. The fourth principle we wish to present, and subsequently explore in more detail, refers to the complex decision and support process, which manages and coordinates the ECOs. Like many other administrative or production processes, the ECO process often suffers the symptoms of long response times. That is, the time it takes between the detection of a need for a change and the time the ECO is finally in place is disproportionate to the amount of work it takes to perform the intermediate steps. For example, Blackburn [6] reports that the value-added time for ECOs in airframe manufacturing is as low as 8.5%; thus, for every day of actual processing time there are 2 weeks of non–value-added time. Most of this non-value-added time is waiting time.

Long ECO lead times substantially contribute to the costs and capacity consumption of ECOs discussed previously. ECO lead time drives ECO cost in several different ways. First, a long response time causes late implementation of the ECO, which is not desirable because of the increasing change costs for tools and interfacing components. Second, having long-lived problems means also having many of them open simultaneously, which can cause substantial problems in coordinating the change efforts. In the days when engineering was still done on drawing boards, this interaction did not exist because once an engineer had taken the drawings from the archives, other engineers were unable to work on the same components. However, in the age of CAD, coordination among engineers is more difficult as now multiple parties can work with the same data simultaneously. Finally, there is a significant risk that the conditions that required a change in the first place will have substantially changed during the course of a lengthy administrative approval process. Thus, once the ECO is approved, it might already be outdated.

Research Objectives

The managerial importance of the ECO process [7,20,28], the long lead times, and the disproportionate amount of waiting time in the life of an ECO [6], together with the scarcity of previous academic work on the ECO process (see previous review) motivate our research efforts. More specifically, we want to address the following research questions:

1. What contributes to the long process lead times of ECOs?
2. How can one speed up the ECO process?

Thus, our first question looks at the sources of long ECO lead times *per se*, searching for the multitude of organizational and technological factors that explain the process problems reported. The second question explores how the process can be improved.

Methodology/Data Collection

To answer our research questions, we have undertaken a detailed study of CCS development during the engineering of a new vehicle at a large European automobile company. The CCS system is one subsystem of the overall vehicle and contains all components related to the climate environment for the passengers, including air ventilation, air purifying, warm-up, and cool-down. We take the CCS system as the basis for this article because it frequently is affected by ECOs. At the same time, it is a system that is well suited to illustrate problems and phenomena that are typical for other development processes as well. To quote a manager in our host organization: "Here [in the CCS system] you find all the problems we have in the development of new vehicles: coordination with other components, coordination of components within the system, and information release to tooling."

Procedure of Data Collection

Data collection was longitudinal, with the first author staying on site for about 4 months on a full-time basis, from October 1996 to February 1997. The longitudinal character of our research enabled us to follow ECOs over time and to gain access to data sources that usually are closed to outsiders. Data were collected from multiple sources, the most important being:

- About 50 semi-structured interviews with engineers and management,
- (Passive) participation in all relevant meetings dealing with ECOs related to CCS development, and
- Data analysis from internal quality and cost control systems that the company uses to keep track of ECOs.

Description of Raw Data

As we will discuss in more detail following, the ECO support process is rather complex and encompasses various activities from different organizational units. At the conceptual level, it is helpful to break this process up into an overall problem solving process and the subprocess that deals with the approval of the ECO. The problem solving process starts with the detection of an engineering problem and includes all activities up to the detailed engineering of a solution and the confirmation that the change solves the initial problem. The ECO approval process is an administrative subprocess of this problem solving that starts with this proposed solution by the engineer and includes all activities up to the management approval of the change. After the change is approved, it usually takes some time to see whether the change indeed solved the initial problem (including lead times of components, time for new tests) and, potentially, the problem solving process needs to start again.

Through the company information system, we have data on over 100 changes related to CCS development, of which we decided to follow 10 in more depth. For those ECOs, we interviewed the individuals involved in the process and developed the history of the change in form of a small case. Although for reasons of confidentiality we are not in a position to provide detailed data on costs or lead times of either problem solving process or ECO approval process, we want to present some aggregated data to illustrate the complexity and time consumption of the processes. Consider the overall problem solving process first. In the project we studied, the overall processing time ranged between 2 months and over 1 year. In fact, a common joke within the company was to point to the "birthdays" of changes when they were over 1 year old. Typically, 5 to 10 persons were involved in the process, including 4 to 7 different departments. In most cases this included the project team, CCS engineering, functional engineering of one or more interfacing components, quality management, production planning, and prototyping.

Of the overall processing time, 1 to 10 weeks were required for the administrative approval process, which typically included representatives from the project team, a CCS engineer, purchasing, and eventually someone from finance/accounting. In this process, the potential costs of a change were estimated and entered into an information system. The costs can be broken up into:

- A one-time investment, typically US$2,000 to over US$50,000, and
- A change in unit cost, typically 20¢ to over $1. Note that this change in unit costs looks relatively

small at first sight, but has enormous leverage, considering the number of vehicles to be sold over the model life time.

For both costs, we observed a strong upward trend over the course of the project. The one-time investment was used to pay for tool changes, which are more costly to implement the closer the project gets to volume production. The change in unit costs followed a similar trend, as the flexibility of an engineer in the search for (cost attractive) alternatives becomes more constrained over time and, thus, frequently only an expensive solution provided the "only way out." This trend is summarized in Figure 1.

Figure 1 illustrates the costs of all ECOs depending on their "arrival" times, for three components. Component 1 had six changes (labeled in the sequence of their arrival as A through F), component 2 had four changes (A through D), and component 3 had eight changes (A through H). The upper half of Figure 1 lists, for each component, the costs caused by each ECO broken down to the three cost categories design (CAD hours), changes in prototype tools, and changes in production tools. For example, change F in component 1 caused US$120,000 for changes in production tools and about $70,000 for changes in prototyping tools. Change B in component 3 caused $10,000 for design work, but no tool changes were necessary as this ECO happened before tools were manufactured.

The lower part of Figure 1 summarizes the total cost of each ECO (the sum of the three categories), depending on its arrival time. Arrival time is reported in the form of three categories: before the start of prototype tools, before the start of production tools, and after start of production tools. For example, change F in component 1 occurred after production tools had been started, and it caused a total cost of $190,000 ($120,000 + $70,000 as explained above). Change B in component 3—escaping tool changes—is associated with a total cost of $10,000. The lower half of Figure 1 shows for all three components that a later arrival time of an ECO systematically and dramatically increase total cost. Moreover, this increase appears to be faster than linear (the cost scale in Figure 1 is logarithmic), although a description of the functional form of the increase is beyond the scope of this article.

Contributors to Long ECO Lead Times: Findings from the Case

Contributors to Long ECO Lead Times 1: Complex ECO Approval Process

As a first step towards understanding why it takes so long from the detection of a problem to the implemen-

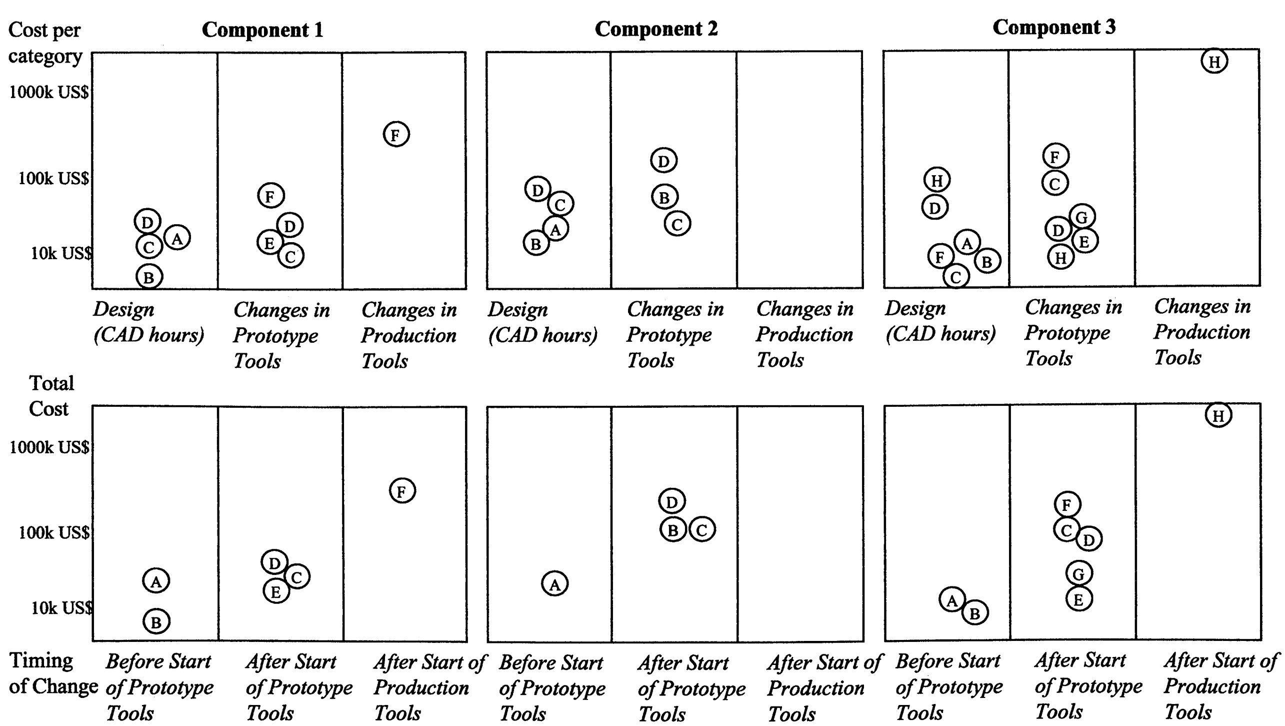

Figure 1. Engineering change order costs as a function of arrival time.

tation of the ECO, we have to understand the steps that are required in between. The mere structure of the process itself already reveals that processing and ECO is a rather complicated endeavor, involving numerous people from a wide range of organizational units.

Consider a prototype test in CCS development where the development organization finds that the rubber water pipes in the engine compartment start leaking because of high temperatures. Figure 2 describes the steps to be taken before the required ECO successfully solves the problem. First, after the problem is detected in the prototype, it typically is entered in a project or quality management system, which allows a precise tracking of the problem. This requires a definition of the scope of the problem and a first assignment of responsibility. In a next step, the problem is discussed in different types of team meetings, including the functional team in charge of the component (CCS development) and one or more cross-functional teams dealing with interfacing components. Once the problem is discussed and clearly identified, it has to be reproduced in a controlled environment to ensure that causes are well understood. Then, alternative design solutions have to be generated and discussed with other interfacing modules, suppliers, and manufacturing representatives. This ultimately results in an ECO. Now starts the ECO approval process, including decisions from project management and potentially cost accounting (administrative approval), several engineering teams (engineering approval), and ultimately of the purchasing department. In the case of a green light for implementation, the purchasing department asks the supplier to include the change in the coming batches of prototype parts. When new parts with the ECO implemented arrive for prototype construction, an evaluation of the new design solution can be made.

The real process is even more complicated than is depicted in Figure 2, which describes a case where the first iteration solves the problem, leaving out possible loops. Each of the activities in Figure 2 takes between half an hour (e.g., decision by project management) and a few days (e.g., reproduction in a controlled environment), but even with some loops in the process, the total time required to perform the activities typically does not exceed 10 days.

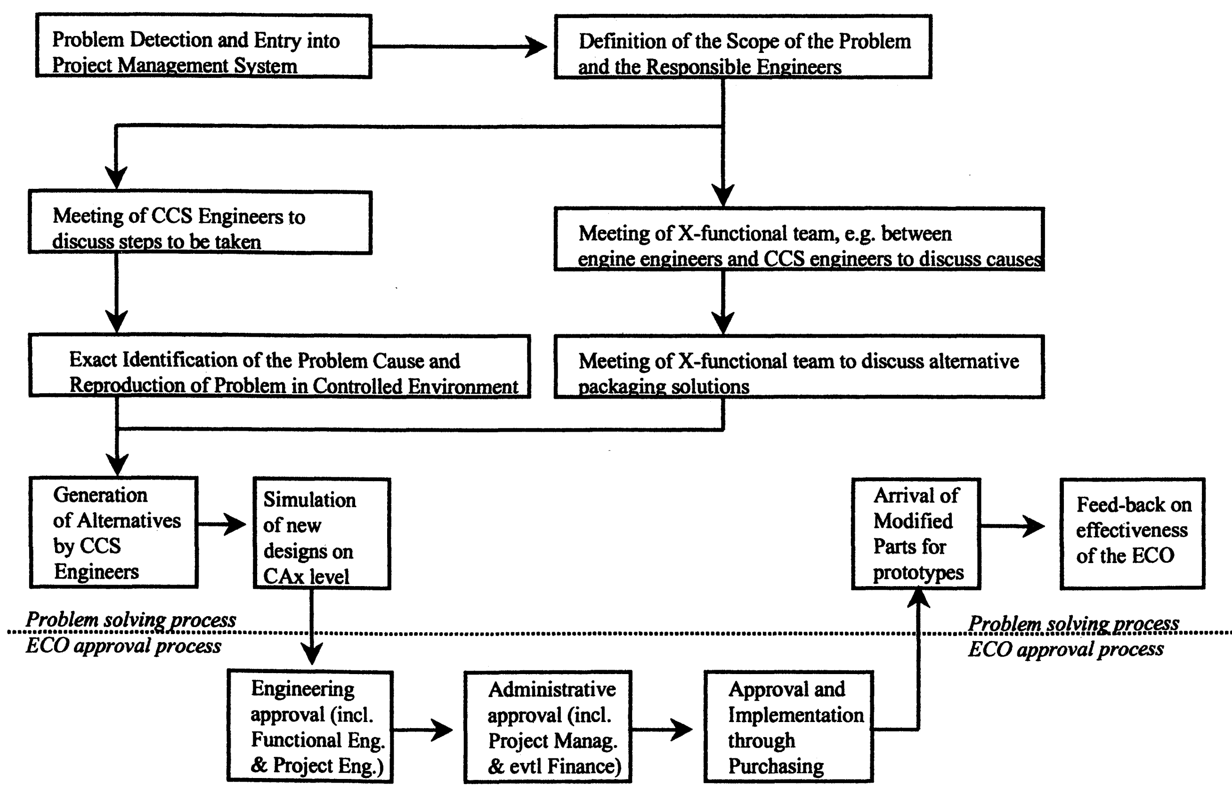

Figure 2. The engineering change order (ECO) process.

Contributors to Long ECO Lead Times 2: Capacity and Congestion

The second reason for the long ECO lead times is related to the capacity of the individual engineer. In the case we studied, this available capacity (typically about 40 hours per week) was consumed by the development project that we focused on (about 50%) but also by a number of other tasks. This included mainly other ongoing development projects, the analysis of problems related to existing products, and advanced research on the component level.

Although the project manager of the project we studied had substantial organizational power and a group of dedicated engineers reporting directly to him, most engineers remained in their functional units and thus worked simultaneously on multiple projects. Engineers referred to the resulting pieces of work coming from several organizational units as "keeping several balls in the air." Several of them reported in interviews that this not only caused problems concerning their management of priorities, but also required them to switch frequently their attention from one project to another, causing a significant time loss from "diving into the project again."

It was not uncommon for an engineer to have backlogs of work sufficient to keep him/her busy for over 1 month, assuming no additional work would be assigned. When the project we studied approached volume production, most of this work was related to ECOs. This created long waiting times that could, depending on the priority of the task, range from 1 week to over 1 month.

Contributors to Long ECO Lead Times 3: Setups and Batching

The batching of orders is one of the oldest principles in management research [15]. In the presence of some fixed setup costs or setup delay, it is advantageous not to process every order individually, but to process a number of them in one batch. This economizes on the number of the times the setup must be performed and thus reduces utilization and congestion. However, batching has a downside stemming from the time a task has to wait in order for its "cohorts" in the same batch to be processed. Thus, an individual ECO is not implemented directly on occurrence, but rather batched with other changes, lengthening the ECO lead time.

In our study of CCS development, we identified four reasons for batching ECOs:

- Batched information release, e.g., because of regular meeting times,
- Batching for coordination reasons, e.g., for prototype building,
- Batching as a result of setup costs for retooling, and
- Batching as a result of mental setups.

The first type of batching has received the most attention over the last years: instead of continuously exchanging information, engineers of different functions meet only at specified milestones or review points to discuss the current status of the project. In the most extreme cases, the whole product engineering information is packed in one batch and then "thrown over the wall" to process engineering. Descriptions of such behavior can be found in Blackburn [6] and Clark and Fujimoto [7]. In our study, we also found some cases of information batching, but batch sizes were typically very small and created delays of only a few days. For example, ECOs were put on hold until the next weekly scheduled meeting between different organizational units. Whereas this type of batching may still be of importance in some industries, we observe a diminishing importance in the automobile industry.

The second type of batching sometimes is referred to as a "synch-and-stabilize strategy" (see [8] for an example in the software industry and [25] for an example from airplane development). Component changes and tool changes can only be implemented during pre-scheduled prototype builds, as a new prototype vehicle cannot be constructed for every single ECO. Typically, a vehicle development project includes about 70 prototype vehicles that are produced in 5 to 10 "waves" spread over a 1- to 2-year period. Because most projects include several thousands ECOs, not every one can be implemented immediately. Instead, some ECOs have to be batched with other ECOs and then implemented in the next available prototype wave. As a result, an engineer asking for permission to change a component by submitting an ECO usually has to specify the prototype vehicles in which the change should be implemented, for example, "change material for cooling pipes from wave 6 onwards." As the number of prototype waves in most development organizations is reduced more and more [38], the average waiting time to the next prototype wave becomes even longer. Thus, this type of batching is likely to become even more important in the future.

Third, batching may be advantageous because of scale economies in implementing ECOs. Consider, for example, the case of reworking injection molds. If every ECO was implemented individually, every time thereafter, the mold would have to be disassembled and transferred to the tool makers where it would be recut, rewelded, or in extreme cases even scrapped. However, if ECOs are batched, several changes can be included in one retooling setup, thus significantly saving on setup costs.

Finally, we have observed a behavior by individual engineers that can be described as "mental setup costs." Take, for example, an ECO that requires a repositioning of the cooling circuit in the engine compartment of a car. Although there are recent attempts in the automotive industry to reduce the number of parts per vehicle [39], today's vehicles are characterized by an extremely high level of technical complexity. As a result, the amount of unused space in the geometry of a vehicle has fallen substantially. This makes the packaging of components (the decision where in the vehicle to place a component) a major challenge and requires the engineer to "dive deep into the problem." This includes loading all the relevant CAD files (in the past, searching out all relevant drawings), linking the CAD data to get a model suitable for the current problem, and cognitively visualizing the complete three-dimensional packaging geometry. Such a setup easily can take 1 whole day, followed by several days during which the engineer is likely to devote all his/her time to the particular problem he/she is working on.

Contributors to Long ECO Lead Times 4: The Snowball Effect

The fourth reason for the long ECO lead times is a result of couplings between the component that is modified and interfacing components or development activities. The stronger these couplings, the more likely is a change in one part of the system requiring change in another part, creating a "snowball effect."

The couplings we observed between activities involved in CCS development can be classified into three groups [31]:

- Couplings between a product component and its corresponding manufacturing process (product–process coupling),
- Couplings between a product component and other components within the same subsystem, e.g. within CCS (intra-unit product–product coupling), and
- Couplings between a product component and other components in different subsystems, e.g. between the steering and the CCS (inter-unit product–product coupling).

Consider product–process couplings first. Examples from CCS development include the coupling between the development of the filter box and the preparation of the corresponding stamping tools, or between the design of the control unit software and the preparation of the required ASIC (application specific integrated circuit) technology. Adding up costs of tool changes caused by the ECOs we studied for one $5-component alone accounted for far more than $100,000, and this is for a part that provides such a small fraction of the value of the overall vehicle.

Figure 3 describes the couplings that exist within the CCS. For example, an increase in the engine efficiency, which translates into less heat produced by the engine, can reduce the amount of warm water that is supplied into the heating circuit. This reduction of warm water in the heating circuit might require a stronger auxiliary heating concept or might reduce the amount of warm water that can be supplied to the main unit (where air is warmed up based on the heating energy stored in the water). Thus, a single change in one CCS component can cause multiple changes in other CCS components.

Third, similar to couplings among components within the CCS, the CCS also has substantial couplings to other components of the overall vehicle. This is shown in Table 1, which shows the strength of the couplings among the major components around the fire wall. These data are based on the judgement of three separately interviewed engineers who were asked to rate the dependencies on a Likert scale between 1 (weak dependence) and 5 (strong dependence). For example, the coupling between the foot controls (D) and the CCS unit (C) is weak to moderate (2). The coupling between the CCS unit (C) and the filter box (I) is strong (5). The stronger the couplings between components, the more likely a change in one component will create a change in the other component[1].

[1] The matrix is based on the concept of the design structure matrix (DSM) as presented in [36].

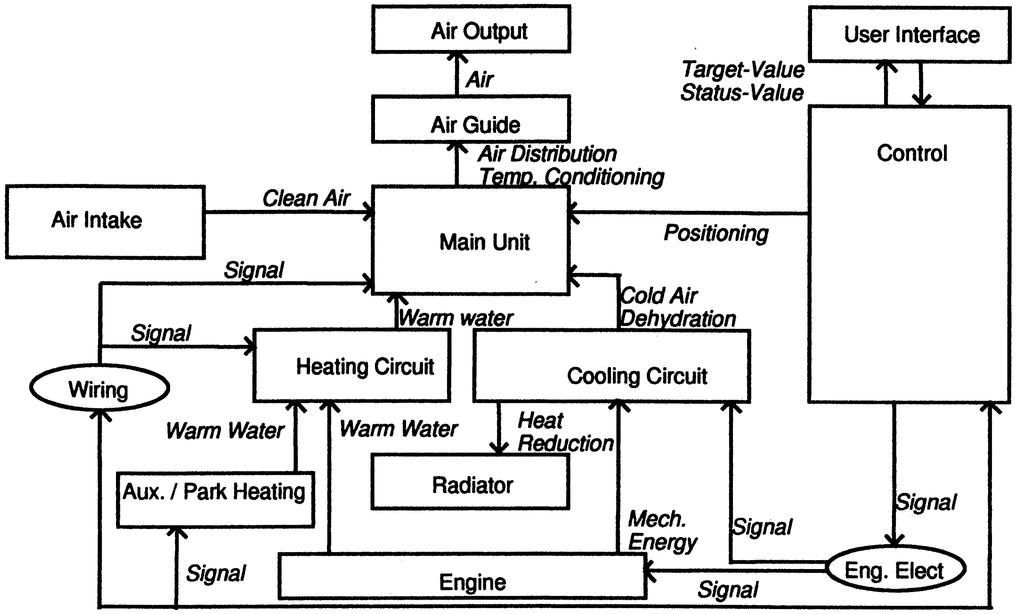

Figure 3. Climate control system architecture.

Table 1. Dependencies Between Compenents

	A	B	C	D	E	F	G	H	I	J	K
A. Fire wall		4	5	4	1	5	5	3	4	3	4
B. Steering			2	3	1	2	5	2	1	1	1
C. CCS unit				2	5	5	5	5	5	5	5
D. Foot controls					1	1	2	3	1	1	1
E. Internal wiring						1	2	2	1	1	1
F. Dashboard							5	2	3	3	4
G. Supporting tube								1	1	1	5
H. Sound insulation									1	1	2
I. Filter box										5	5
J. Wiper drive											4
K. Air guide											

Larger numbers indicate stronger couplings.

Contributors to Long ECO Leadtimes 5: Organizational Issues

First, in the development organization we studied, we found a *dominating culture of cost management* and, at the same time, relatively little emphasis on time management. This was mirrored in the measurement and incentive mechanisms in place, which were strongly targeted toward staying within the budget. If an engineer created a design solution exceeding the target by a few cents, multiple alarm mechanisms were triggered, ultimately escalating all the way up to senior management. If, however, some crucial information was provided with several weeks' delay, no measurement system was in place to detect the delay problem. Another example of this cost culture is the rather complex ECO approval process, some aspects of which we have discussed previously. Multiple levels of signatures were required to spend extra money, but, again, no signature was required if time-critical tasks were not completed on time. As a result, the development organization only recently has emphasized the importance of short ECO lead times. Prior to that, time performance could not be measured, and ECO management did not receive the same attention as it does today.

Second, and partly related to the first point, we found a substantial *cultural difference between the two engineering groups* involved in the process. From previous studies, we had expected to find such a culture gap between product and process engineering, but these two groups were surprisingly close to each other. However, a gap was found between the group of engineers in charge of integrating the process and the engineers responsible for the actual detailed engineering. The first group, in charge of integration, was relatively small (about 30 to 40 people), fully dedicated to the vehicle project, and reporting through a flat hierarchy to the overall vehicle project manager. Although almost all of them were electrical or mechanical engineers with a passion for cars, they resembled, in many ways, a typical management profile: using cellular phones, dressing in suits, using E-mail and intranets, permanently communicating (including

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shouting from one corner of the building to another), and sharing an open office space with no walls except for those enclosing a few meeting rooms. Despite their technical expertise, surprisingly few of them were skilled in using CAx technology[2], which prompted—from the second group—the nickname "A4 engineers" (which refers to the fact that in the "old days," sophisticated engineering drawings were done on large sheets of paper clipped to large drawing boards, whereas administrative procedures were written on A4-format paper). The second group (detailed engineering) was part of the functional engineering organization, had the same engineering background, the same passion for technology, and the same pay level. However, there was a different atmosphere predominant in this part of the company: long corridors of closed doors, virtual silence in the buildings, and people sitting behind large drawing tables now used as room separators. This difference in culture was especially apparent when it came to agreeing on priorities between project organizations and the functional organization, which served several projects simultaneously. Of course, the project engineers had a clear view of what was important: their project and, most importantly, ECOs! The functional engineers, however, had plenty of other activities to work on, including other vehicle development projects, consultation with after-sales services, pre-development projects, and so on. As a result of the cultural differences, project engineers often had the impression that functional engineers were unwilling to respond to their requests. This led to increased tension between the parties and frequent interventions on the part of senior management for minor problems.

Third, we observed a lacking *awareness of the consequences of an ECO*. Talking to both sides, engineers requesting changes and engineers being affected by these changes, we observed the case where a CCS water pipe was to be repositioned to go through the fire wall at a point 2 cm away from that marked on the initial plan. Asked for the cost of the change, the ECO-requesting engineer estimated about US$10,000: "Just some minor adjustment in the stamping tools." The response from the engineer in charge of developing the fire wall, who was affected by the change, fundamentally differed: "Some holes we can change, but not this one. And, most importantly, not now. Changing the hole today will cost us several US$ 100,000 because the anchoring of the car on the assembly line is affected."

[2] We use the acronym CAx to include technologies such as computer-aided design (CAD), computer-aided engineering (CAE), and other similar engineering tools.

Discussion and Improvement Potential

Contributors to long lead times 1 through 3 (that is, a complex approval process, capacity and congestion, and setups and batching) are closely related to the management of business process flows [4,13,18] or business process reengineering [12]. Process redesign rules for speeding up processes are very well accepted in manufacturing and service operations (see [21] for an overview), but to date have found little attention within product development processes. Based on our findings, however, several redesign rules do apply as is outlined following.

The *complex approval process* offers the potential to eliminate unnecessary steps (such as oversight, bureaucracy, or reconciliation of data) and handoffs among parties. Outlining the detailed process map as given by Figure 2 provides a first step into that direction. In particular, as new technologies (such as electronic data transfer, E-mail, or computer simulations) become available, old process structures may become obsolete. For example, computer-based problem solving tools with integrated simulation capabilities (on which the company is working) would allow a combination of the CCS engineering and CCS simulation, eliminating the corresponding handoff and in-basket. Handoffs also can be eliminated by organizational changes rather than technology: allowing an engineer to handle an ECO all the way through without having to ask for intermediate checkoffs from management requires not technology, but training of the engineer (in terms of quality, process knowledge, and communication) and a willingness of management to delegate and check final results rather than process details. Experience from manufacturing and service industries has shown that such organizational changes are sometimes more difficult to achieve than technology changes [12].

Capacity and congestion effects very often lead to long throughput times. However, a number of qualitative process specification principles have emerged, centering on *reducing utilization and reducing variability* (see [2,3,21] in the context of product development). Whereas our host organization made it clear that increasing capacity through hiring was out of the question, utilization still can be reduced through flexible capacity (working overtime just when the effort is needed), better data processing systems and simulators (automation), and limited pooling of engineers to enable them to help each other out when one is overloaded and the other has some slack. Detailed improvement programs for capacity and congestion, as well as batching, are discussed in greater detail in a companion article [23].

Batching is closely related to the capacity and congestion problems discussed previously. In effect, batching reduces utilization because it economizes on setups. The benefit is that utilization and thus congestion is reduced, but the tradeoff is that one task may have to wait for its "cohort" tasks in the same batch to be processed as well. A simple lesson is to "split batches," i.e., educate engineers to not "sit on the ECOs" until the whole batch is finished, but release them one by one. A stricter measure is to force fast response times ("this has to be solved within 1 week," analogously to the "synch-and stabilize" process in software development [8]). However, as problem solving can never be exactly planned in engineering, the danger of this strategy is that engineers do "token efforts" to pretend they are working on the problem. Moreover, if an engineer is already heavily loaded, the extra setups arising from the fact that batches are "forbidden" may push the load so high that extra congestion and waiting more than outweighs the benefit. In either case, similar to manufacturing, setup times should be seen as an improvement potential rather than as fixed constraints. Our list of setup causes suggests various ways of reducing setup times and thus shortening the delays from batching.

The fourth contributor to long lead times, *couplings and snowballing* of ECOs to other subsystems, is essentially determined by the architecture of the car, which is settled before development begins. Once the project is under way, the couplings can no longer be influenced. However, the negative consequences of the couplings can be reduced. Engineers across groups need to systematically identify where the key couplings lie. Table 1 provides an example of such a systematic identification. In addition to acquiring this *process knowledge,* engineers should be held responsible for *ensuring fast feedback and turnaround* for those ECOs that affect key couplings and are, thus, likely to snowball. This includes an immediate communication of all problems that affect critical couplings, and a high prioritization of the resulting ECOs. This generates faster feedbacks and turnaround times for these critical ECOs, which reduces their snowballing into a large set of other components in the car.

The last contributor to long lead times, *organizational issues,* also is connected to process knowledge. First, knowing the impact of an ECO in terms of cost across the whole car is connected intimately to knowing the key couplings. Currently, engineers tend to make decisions based only on the myopic considerations of how this affects them and their group, as well as the unit cost of the component in the car.

Moreover, there is a lack of simple economic models of the *value of time,* which engineers can use operationally to make tradeoffs between further improving the component or interface and finishing later. Costs are easy to measure, whereas the effect of being late by 1 week is difficult to quantify. This lack of easy-to-use models is part of the reason for the cost-focused culture that we observed. There are a few attempts of providing time-value models [5,28,37], but the first is too specific for one industry (with a certain product life cycle), and the other two are aimed at strategic product design decisions. Operational time-value models that can support the engineer solving an ECO have yet to be developed. Once such models exist, the engineer can explicitly evaluate the tradeoff between finishing the task faster and, for example, redesigning a component one more time to reduce its manufacturing cost.

Finally, the cultural differences across functional groups have been documented repeatedly in comparing engineering and manufacturing [10] or development and marketing [29]. In our case, we observed similar differences even *within* engineering, namely, between the functional groups and the project management engineers. The recommendations from previous studies apply [24,29], including frequent contact and communication, personnel rotation across groups, and clear responsibilities/clear communication protocols to make communication easier.

Conclusion

In this article, we have outlined a process-based view of ECO management. We have shown that many of the problems related to ECOs have their roots in a complicated and congested administrative process. We have identified five contributors to long ECO lead times in our study: a complex approval process, snowballing changes, scarce capacity and congestion, setups and batching, and organizational issues. Understanding these five contributors allows managers to focus their improvement efforts and to follow some of the improvement opportunities outlined. A further, more detailed study of congestion and batching effects is included in a companion article [23].

The major advantage of our case-based approach is that it enabled us—free of any bias from problem framing—to identify the contributors to long ECO lead times. Spending over 4 months on site and in total more than half a year in close contact with the company allowed us to collect detailed data on costs, throughput times, and organizational issues. This data usually would be inaccessible to outsiders.

However, our approach also has some shortcomings. The generalizability of our findings to other product development organizations possibly is limited. Our case is based on a rather complex and mature product, and future research needs to replicate our findings in other settings.

In addition to replicating parts of our research for increased generalizability, we see other promising avenues for future work. First, the role of CAx technologies in managing ECOs deserves further attention. Such technologies may, in the future, be capable of automatically detecting problems in the current design (to some degree, this capability already exists, e.g., for fit problems in packaging). Automatic problem detection and the ease of including changes in virtual prototypes will bring about a fundamental reconsideration of the ECO process. Second, organizational integration does not automatically follow the introduction of such new powerful technologies. One manager at our host organization commented: "We have all the tools, but we don't know how to make our people use them all effectively." Further study is needed to understand how the cultural divide between organizational units can be overcome and how an overall culture of process management can be achieved.

A resulting more detailed understanding of the ECO process will allow development organizations to reduce the negative impact of multiple late changes and to move toward achieving both product and process excellence.

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