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CHARACTERIZING THE DYNAMICS OF DESIGN CHANGE

Afreen Siddiqi[1], Olivier L. de Weck[1] , Bob Robinson[2] and Rene Keller[2]
(1) Massachusetts Institute of Technology, USA (2) BP, UK

ABSTRACT

Engineering design changes play an important role in improving the technical design and ensuring eventual success of the system. Most of the research related to design changes has been traditionally focused on studying the management of the change process, prediction of change propagation and dynamics of rework in projects. This study conducts an empirical investigation of engineering design changes. The changes are described through the attributes of change requests volume, time, costs, and location using a large dataset of 1147 records spanning five years from 2003 to 2007 in an actual multi-year, multi-billion dollar engineering project. A few theoretical generalizations are proposed regarding the dynamics of change volume and costs. The results of the data analysis are used to illustrate how knowledge of meta-change activity and attributes can be used both for informing resource allocation and planning decisions for project management, and improving system design.

Keywords: design change, change dynamics, change volume, change costs, change management

1 INTRODUCTION

Design changes are an essential part of system design, development and implementation. In fact, changes are the rule, not the exception in the product development process [1]. Changes can arise due to a number of reasons such as new requirements (typically due to new customer needs or market trends), errors or infeasibility in an initial design, cost reduction or process improvement measures etc. Since changes form an integral part of the development process, it is important to understand and manage them well. Otherwise, with inadequate control and poor management of design change there can be adverse effects on project cost, schedule and ultimately even performance and safety.

Changes in the design and development process can be described through many different attributes. Some key descriptive attributes include the final approval state, which systems, sub-systems, or components initiate the change and which are the ones that are affected by it, how much does the change cost to implement and perhaps what is its anticipated impact on lifecycle costs (during operations and maintenance) or net present value (NPV). Other important information includes the reason for initiating the change, the change owner (person who identifies or request the change) and so on. Fig. 1 shows an Object-Process Diagram (OPD) [2] of a simplified typical engineering design change process. The figure shows that due to various causes a design change may be initiated that results in the issuance of a ‘design change notice’. Some attributes of this initiation process include the date when the change is initiated, the estimated cost, or relevant subsystem. The change notice is then processed and verified. This operation adds additional attributes to the change notice such as that of an approved cost and final status date. The verification and review process may either approve or reject the change. In case of approval, the change is executed which results in modifying the state of some part of the system. The change implementation also affects the total cost and schedule.

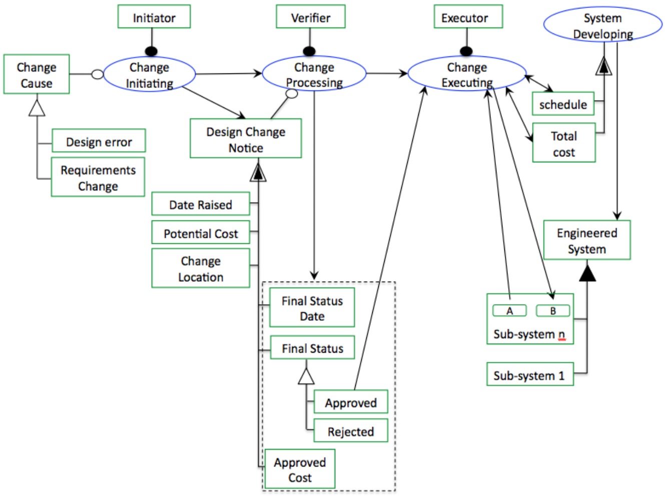

Figure 1. An Object-Process Diagram of Design Change

In large complex systems, comprising of many sub-systems and components, involving large number of design engineers, part suppliers, integrators and so on, effective management and handling of design changes can be particularly difficult. A number of researchers have devoted attention to studying and improving the change management process [3] for such systems. In these efforts, the focus has been on creating methods that can streamline the processes of how changes are initiated, recorded, communicated, reviewed, approved, and implemented. Another area of particular research attention has been on studying and predicting change propagation. In complex systems, with a large number of structural, functional and informational interdependencies, it is often difficult to fully anticipate the impact of a particular change. An insufficient understanding of what a particular change may do to the rest of the system, however, can cause unplanned cost increases, delays and unexpected functional/performance issues. Various methods using risk matrices [4] and networks [5-6] have been developed towards a goal of better understanding and predicting the impact of changes.

Within the larger body of research on engineering design process in general, there is a significant amount of work that has been carried out in the context of design iteration [15]. In general, iterations are the repeated cycles of design activities that attempt to converge to a feasible, ideally optimized, design that satisfies the given requirements [7,15]. The research on design iterations, while specifically includes the aspect of re-design due to errors or changed requirements, mostly focuses on the product design development process. The emphasis is on convergence of information across design teams, and the end stage is a completed, feasible design. The research on design iterations thus essentially focuses on the dynamics of the emergence of a feasible design. Design changes that may arise during the implementation, construction, and operation stages have typically not been factored in.

In the project management literature, the design change issue is considered through the 'rework' aspect of project dynamics, that includes the notion of changes that need to be made to previously completed work due to errors or new requirements [8]. In these models, changes that result during the testing, integration and implementation phases are also included. Changes in these phases of the system development cycle have in fact been found to account for a significant portion of the overall rework activity in some cases [5]. The project rework cycle has been studied in depth from a management perspective, where the key variables of interest are number of staff, productivity, percent work completed, and so on [16]. The rework activities, are included in the project dynamics model usually as a lumped entity that impact fraction of actual work completed and project completion time and costs. In this work, we seek to investigate the rework from the system's technical design change aspect.

In general, while significant attention has been devoted to studying the change management process, change propagation and the role of rework in overall project completion and cost, there has been somewhat less attention towards characterization of the underlying nature, types, and dynamics of the design changes themselves. Such an understanding can be very useful for removing systemic problems in the design, reducing change activity in future projects, and finding targets for implementing flexibility in the system. It has been noted that, “most companies focus only, if at all, on improving administrative change process and do not incorporate the idea to implement changeability into their system architecture” [1].

In this context, we create an initial framework for studying the collective change activity that can provide practical information for design improvement and project management. We analyze a large dataset of design changes related to a multi-billion, multi-year project of designing and building an off-shore oil and gas production facility. We study the evolution of change activity over the project timeline from initiation to commissioning, and analyze the time-based behaviour of change costs and change location (sub-system).

2 CASE STUDY: OFF-SHORE OIL AND GAS PRODUCTION SYSTEM

The project data analyzed in this work relates to the BP Angola Block 18 Greater Plutonio development for oil and gas production. This offshore development area is located 16 kilometers northwest of Luanda and is comprised of five fields in water depths varying from 1200 to 1450 meters. The Greater Plutonio accumulation was discovered in 1999-01. It had a 3.5 years development timeline and first oil was produced in October 2007. The initial CAPEX was approximately US $1 billion, and capital expenditure over the life of the fields is estimated at US $4 billion [9-10]. The facilities contain 43 wells, of which 20 are producers, 20 are water injectors and 3 are gas injectors. The wells are connected through a large subsea system to an FPSO (floating, production, storage, and offloading vessel) for fluid processing and export. The FPSO is 310 meters long with an oil storage capacity of 1.77 million barrels and oil processing of up to 240,000 barrels per day (see Fig. 2) [9-10].

Figure 2. Floating Production Storage and Offloading (FPSO) Vessel in Angola, Africa [9]

The scope of the Greater Plutonio project that was analyzed in this work was the design and build of an FPSO facility. Any design changes that were initiated and processed during this effort were recorded through Design Change Notices (DCN). The information recorded for every DCN comprised of 30 different fields that included DCN sequence number, Date Raised, Final Approval Status (approved, rejected or withdrawn), date of final status, Originating Discipline (such as structures, instrumentation etc.), Final Approved Cost, Change Owner etc.

All DCN information was compiled in a database that had a total of 1147 records spanning five years from 2003 to 2007. Since the focus of this work is on time, cost and location, the specific fields that were analyzed were *Date Raised* and *Approved Cost*. Since the data set did not include complete information regarding the particular sub-systems associated with the change, a higher-level categorization of ‘*Originating Discipline*’ for which data was available for most records was used as a substitute for location information.

3 DATA ANALYSIS AND DISCUSSION

While there were a number of attributes recorded for each change notice, we analyzed the time behaviour of three quantities: change volume over the entire project timeline, change cost and change location (as described by the discipline). We also investigated the processing time of change notices since that is an important parameter that can greatly influence the dynamics of the change activity, design maturity and overall project completion. The following sections discuss the analysis in detail.

3.1 Change Volume

The dynamics of change volume were investigated by plotting the number of DCNs that were raised on a quarterly basis. Fig. 3 shows the rate (on a three-month basis) at which change notices were registered. Some key project phases have also been marked for reference. The graph essentially shows a ‘ripple’ pattern (see Fig. 4), which has been previously theorized to describe change activity of a well-behaved design effort [11]. In general, there can be change ripples, change blossoms, or change avalanches. Typically, well-understood, predictable processes cause change ripples. “They begin with large number of changes initially which may also result in a degree of change propagation. However, the total effort required in the redesign decreases over time.” [11]. Fig. 3 shows empirical evidence of the ‘ripple’ pattern for this project. The largest (and initial) hump in the ripple pattern is during the ‘detailed design’ stage. The number of changes starts to fall once the ‘fabrication’ stage commences. However, it is noteworthy that changes were still made even during fabrication and to a lesser extent during commissioning and initial operations.

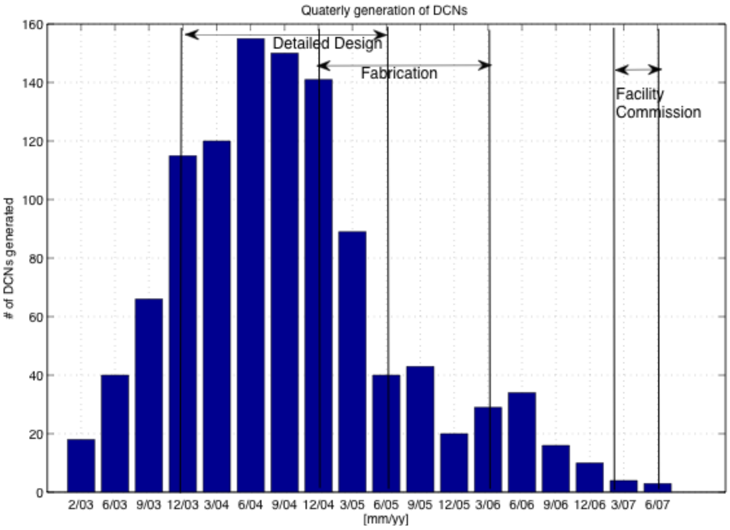

Figure 3. Design Change Volume on a Quarterly Basis

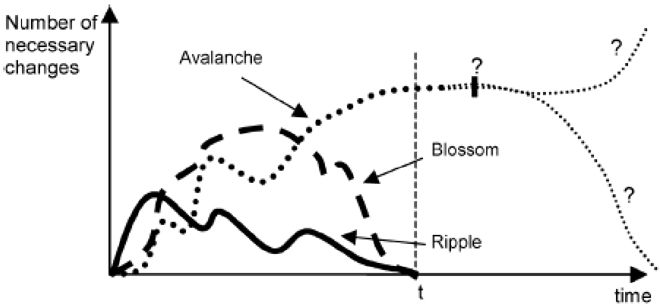

Figure 4. Types of Change Effort Over Time [11]

Based on the shape of the change activity (in Fig. 3), it appears that this process is one in which there is an initial increase up to a point and then eventual decrease (of change notices). The rate at which change notices are generated (shown on a quarterly basis here) keeps on increasing till the mid-point of the detailed design phase. After that there is a downward turn and the rate starts to decline until it eventually falls to zero after the facility has been commissioned. This behaviour suggests that it maybe possible to describe this change activity with the logistic function, which is often used to describe population dynamics in an environment of finite resources or ‘carrying capacity’ [12]. In population dynamics, the rate of population growth increases with more and more individuals, however after a certain point, once the carrying capacity of the environment such as food and other resources become insufficient, the growth rate decreases and eventually falls to zero.

In the context of design change, the finite resources may be considered to be that of money (project budget) and time (schedule deadlines) that limit the extent of change activity. Using the formulation of the logistic function as shown in Eq. (1)

$$\frac{d}{dt}P = rP\left(1-\frac{P}{K}\right) \tag{1}$$

where P is the population (or total number of DCNs raised), K is the carrying capacity and r is the growth rate. For r=1:

$$P = K\frac{e^t}{e^t + e^c} \tag{2}$$

Fig. 5 shows the comparison between the logistic curve (as described in Eq. 2) and the cumulative number of DCNs (‘population’) in the project. K was set to the total number of DCNs that were raised (1147), and a value of c=3.5 was used to get the fit shown in Fig. 5.

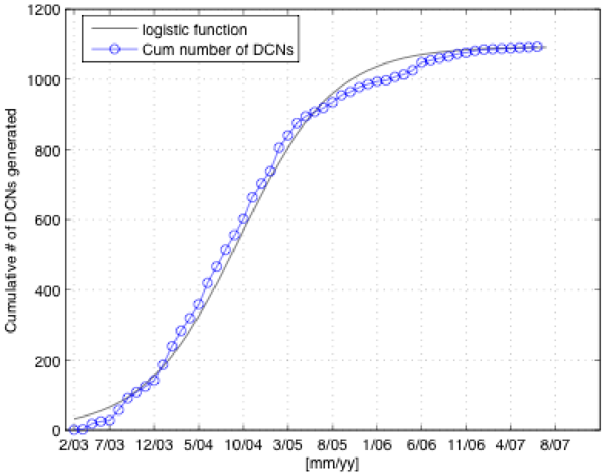

Figure 5. Comparison of Cumulative Change Volume with a Logistic Curve

One can imagine that in a project that is successfully completed, the design change activity may likely follow a curve that can be described by the logistic (or some other related growth-model) curve. The initial increase in rate of change generation can be attributed to early design efforts that seek to refine and finish the design and in the process generate more and more changes. There may also be some change propagation going on that contributes to this increasing rate. Eventually however, the design matures enough that fewer and fewer changes are generated and the design stabilizes with essentially no further change activity in the end. On the other hand, a project in which the change activity snowballs and creates an ‘avalanche’ as shown in Fig. 4, the curve may be a pure exponential. Such a project never stabilizes and may eventually fail to converge the design. In future work, we will analyze datasets of more projects to investigate if empirical models of change activity can be built based on Systems Dynamics concepts such that the parameter values (of K, c, r etc.) can be linked to project outcomes (e.g. completion time, cost implications etc.). A point of caution, however, is that simply because a project is completed on time does not necessarily mean that the project was successful (as judged by the relevant stakeholders involved). The fact that the changes stabilize and decrease over time may simply mean that a successful effort was made to respect the completion deadline.

3.2 Change Processing Time

An important aspect, when analyzing the dynamics of change, is the processing time of the DCNs. We estimated the processing time for each DCN by taking the difference of the Date Raised and Final Status Date. Fig. 6 shows the distribution of the processing time. The top plot shows the complete data in which the processing time in days is plotting for all the DCNs. The bottom plot shows the same data in the form of a distribution. It is found that most of the DCNs are processed within two weeks (13 days or less). There are however some that take much longer (up to six months in a few cases). Those DCNs were investigated in more detail, but no explanatory trends were found. The Potential Cost and discipline of those DCNs was analyzed and no correlations were found. It is likely that the long processing times for those few cases may simply be due to various un-related, and non-systemic causes.

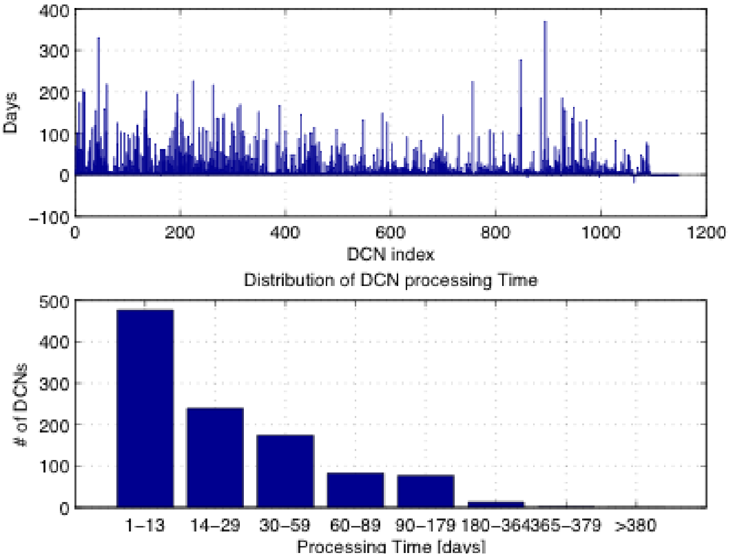

Figure 6. DCN Processing Time Data and Distribution

The processing time along with change volume play an important role in the maturity and stability of the system design and overall project. If the rate at which the changes notices are being filed is higher than the rate at which the changes are processed, backlogs can build up that can impact the rate at which the design of the system will eventually stabilize. Large backlogs can be detrimental since they can cause even more changes and rework to be generated. A backlog would indicate that while some engineers have raised a request for a change (based on an error they may have found or changed requirements etc.), others are still using and developing their designs on older information/specifications.

For the case-study dataset, it was found that the change notices processing rate was well behaved as compared to the change generation rate (as can be seen on a monthly basis in Fig. 7). The inset figure in Fig. 7a is the cumulative graph of the changes that were raised and the changes that were processed to provide another view of the data. It can be seen that the graphs have very similar shapes, with the DCNs processed curve (in black) simply shifted to the right on the time axis as compared to the DCNs raised curve (in blue). Note that the two curves do not meet at the end since some DCNs had missing data for ‘final status date’ field and therefore the final cumulative value of DCNs processed is a bit smaller than that for DCNs raised. The net DCN activity per month (the difference between DCNs raised and DCNs processed) is shown in Fig. 7b, and the backlog (number of DCNs that need to be processed) each month is shown in Fig. 7c. The backlog does not reach zero due to the missing ‘final status dates’ in some records. A review of those DCNs shows that of the 27 such records, 20 were associated with DCNs that were withdrawn, and 7 had been approved (but final status dates had not been filled in). On the whole, it can be seen that the number of DCNs to be processed accumulates in the early part of the project, reaches a peak and then decreases towards the later part.

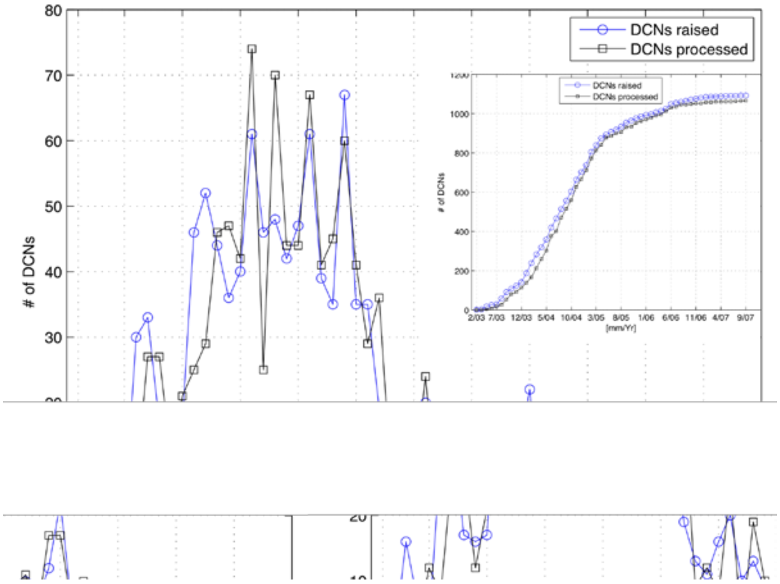

Figure 7a. DCN Generation and Processing Rates Comparison

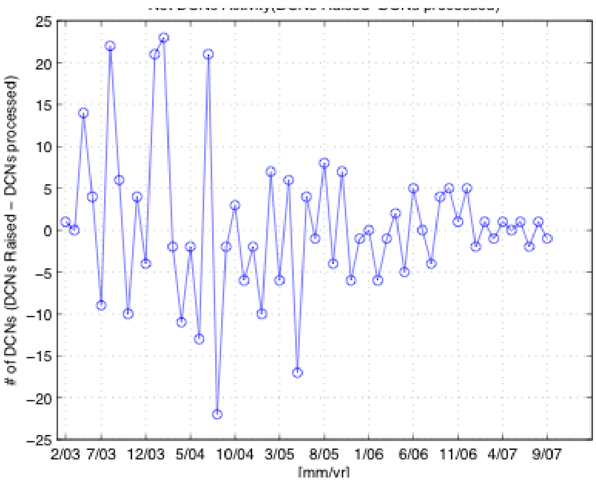

Figure 7b. DCN Net Activity

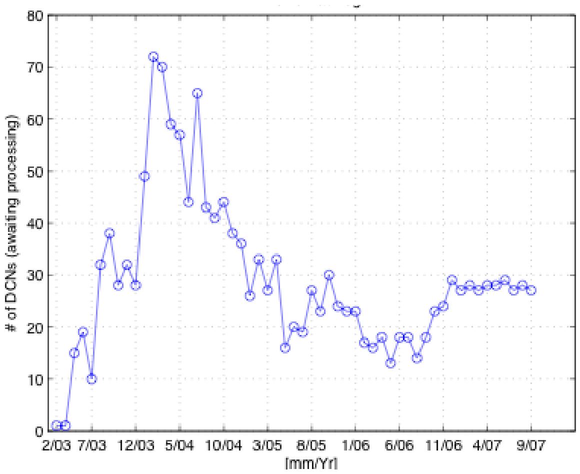

Figure 7c. DCN accumulation (backlog) for processing

3.3 Change Costs

The time-based behavior of change costs was analyzed in two ways. First, the evolution of different cost types was determined (shown in the inset of Fig. 8), and second the overall cumulative behavior was analyzed.

Based on the Final Approval Cost, the DCNs in the dataset were found to be of three different types. Each DCN either had a cost increase, a cost reduction or was of neutral cost (i.e. no change in cost relative to the initial estimate when the change request was first raised). The inset of Fig. 8 shows this classification for the approved DCNs that were raised each month from February 2003 through July 2006 (the period for which DCN cost data was available). It can be observed that most of the cost reduction effort took place in the early part of the project. The cost reduction activity (green portion in the stacked bar plot) almost completely finishes by the time fabrication starts in November 2004. After that point the DCNs mostly involve cost increases with reducing numbers of neutral cost changes.

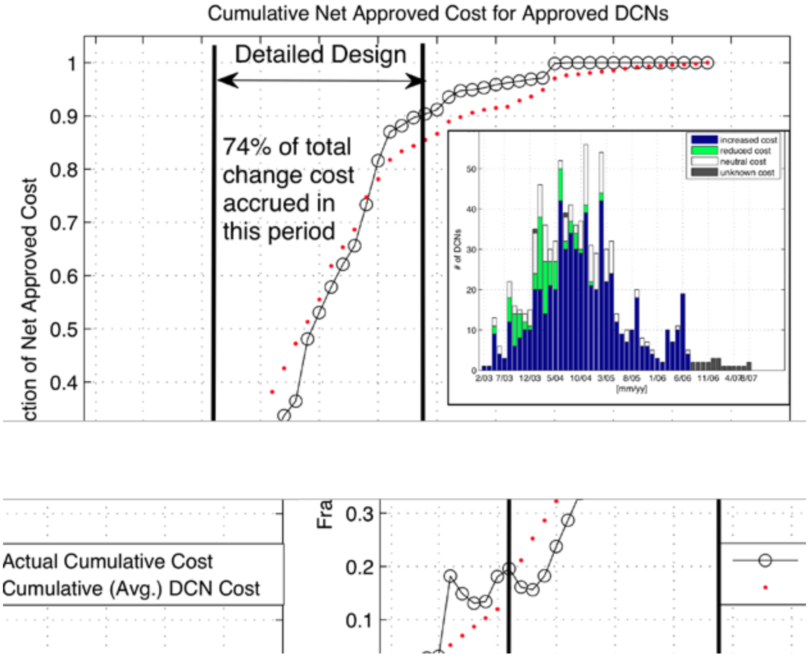

Figure 8. Change Costs Accumulation over Time

The cumulative cost profile in Fig. 8 follows an ‘S’ curve – flatter in the beginning and end and steeper in the middle. The S-curve is well understood in systems engineering and in systems dynamics, wherein it is known that a typical cumulative cost profile over time for a project follows an S shaped pattern. This pattern results from the fact that initially there is a slow pace of expenditure at the start of the project that is then followed by a period of rapid consumption of resources (usually 70% as a rule of thumb). In the end the rate tapers off as the project concludes. While in general the S-curve has been known to describe cost curves this result empirically shows a ‘S’ curve for design change costs as well. In this particular case, 74% of the total approved DCN cost was accrued during the ‘detail design’ phase of the project. This S-curve for cost is obviously related to the S shaped change volume curve discussed earlier in Fig. 5.

Fig. 8 also shows the computed cumulative cost by using the average cost per DCN. The dotted curve thus obtained shows good agreement in the middle part of the S-curve. The difference between the two curves is greater in the initial ramp up period. This is due to the approval of some high cost changes (on the orders of millions of dollars) early on. A few decreasing trends in 2003-04 time region are due to some large cost reduction changes as well that reduced the net change costs on those respective months. The average cost curve therefore deviates from the actual cost curve in that region. But on the whole, the average cost cumulative curve seems to be a good representation of how the cost profile develops over the project’s timeline.

In future work these results will be compared against data from other projects to see if similar patterns emerge. If this is found to be a recurring trend, the results can help in informing planning and resource allocation decisions. Furthermore, it will be interesting to investigate how projects with breakthrough innovations compare with those that have incremental innovations.

3.4 Change Location

Analysis of change location can be very useful for informing future improvement measures to a system design. Indeed it has been noted that, “completed projects should be analyzed with some questions as: What kind of elements were changed most frequently, when were these changes initiated, and who was initiating them? An analysis of the parts most frequently changed allows selective support of development tasks and well-targeted actions to reduce changes”. [1]

In the dataset of the project analyzed in this study, the change records provided information regarding ‘originating discipline’. There were a total of 22 different disciplines, listed in Table 1, associated with the 1147 DCN records. The originating disciplines for each change record were used as a proxy for change location.

Table 1. Change Originating Disciplines

AR	Architecture	MT	Materials Engineering
CM	Commissioning	OP	Operations
EL	Electrical	PI	Piping
EM	Estimating	PM	Project Management
HU	Hull	PR	Process
HV	HVAC	SA	Safety
IC	Instrument/Control	SS	Subsea
IM	Integrity Management	ST	Structural
IN	Instrumentation	SY	Systems
ME	Mechanical	TE	Telecommunications
MR	Marine	UR	Umbilical and Risers

Fig. 9a and 9b collectively show the number of change notices filed for each discipline on a yearly basis. The disciplines have been organized in alphabetical order and have been split into three graphs for easy viewing. It can be observed that most disciplines have highest number of changes in the beginning of the project (years 2003-04), while some have a fair percentage of their total changes well into the later part of the project (2006-07) such as IN, TE, EL and OP. It is interesting to note that the 'hotspots' in terms of time are different than those in terms of total DCNs aggregated over entire project. For 2003-04 period, MR, PR, ME were the top disciplines. These can be considered the 'early bloomers' that contribute the most to change activity in the early part of the project. For years 2006-07, TE, IN, EL and OP dominate in terms of most changes. These can be thought of as the 'late bloomers' that show up for changes late in the project. To some degree this may be explained by the nature of the disciplines, and the system design. For instance, note that the late bloomers involve telecommunications, instrumentation, and electrical systems. These disciplines relate to many components that may typically be the last to get integrated with the rest of the larger, structural elements.

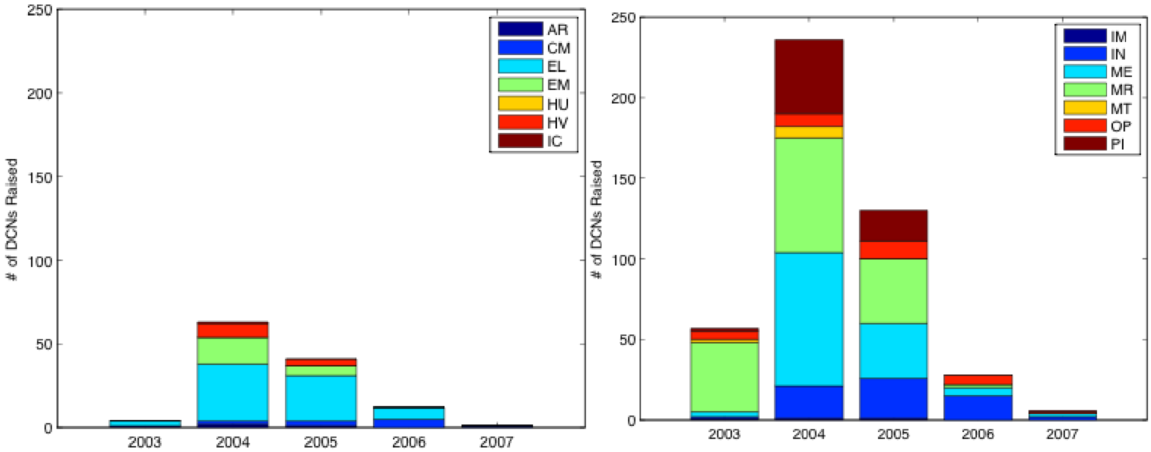

Figure 9a. Yearly DCNs per Discipline: AR - PI

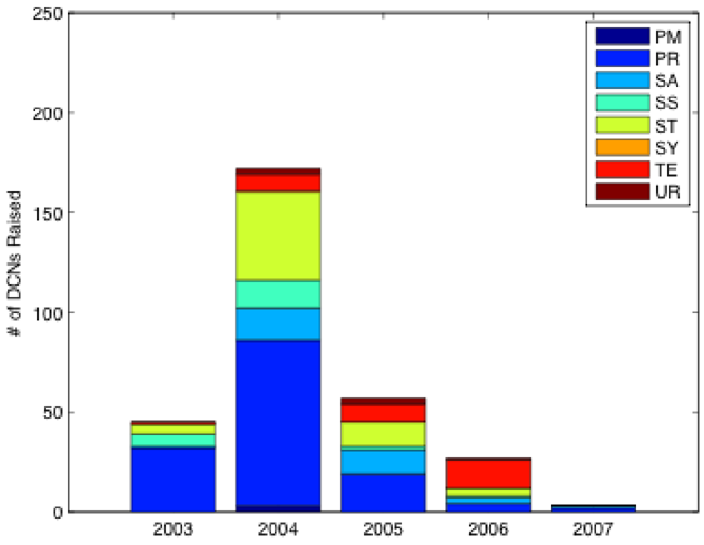

Figure 9b. Yearly DCNs per Discipline: PM - UR

4 SUMMARY AND CONCLUSIONS

Research efforts on design change have typically been focused more on procedural improvements and efficiency gains of the change management process or prediction of change propagation. It has been noted that design changes are often considered a problem, rather than an opportunity [13]. In order to convert changes from being problems to becoming opportunities, it is necessary to construct an understanding of change attributes and their temporal behavior. In this work we suggest an analysis approach that seeks to create a theoretical understanding of the time based behavior of change activity as described through its rate of generation, cost and location. An understanding of the nature of the underlying characteristics of these change attributes can provide a useful basis for constructing practical tools and methods for better management and design improvement. For instance, assessing the cost impact of changes can be very beneficial, since it provides a basis for valuing change activity against design improvement and system performance. Similarly, an understanding of how change costs typically accrue and how different sub-systems behave in terms of change activity over time, can help in resource allocation, planning, and budgeting. For example, in this case-study it was found that Marine, Process and Mechanical disciplines showed greatest change activity early on in the project, while Telecommunication, Instrumentation and Electrical showed their largest change activity in the later years of the project. If this pattern is found in other similar projects in the firm, it can form the basis of formulating more effective staffing and budgeting plans.

Actual change data of large projects is rarely found in the published literature. The analysis presented here can therefore serve as useful information for other studies on engineering design change. The characterization of patterns can potentially serve as a basis for comparison with other system design and development projects of the same type in the future. A key requirement for conducting such comparative studies will be the availability of design change data sets that have sufficiently detailed information that can be readily analyzed. Such data has been recorded (or is at least recoverable) in software systems (where modifications and changes to the internal code are documented through source control tools). In mechanical design, many firms are also using increasingly sophisticated systems for recording information of design changes for better preservation and traceability of their product design evolution.

Using data from many different projects, one can formulate predictive measures, or *leading indicators*, regarding project performance based on its engineering change activity. Recent work has proposed using change activity as a leading indicator measure for making projections of future system performance and for assisting in taking corrective actions to minimize rework [14]. In future analysis, with additional data sets, specific focus will be given on isolating patterns that can serve as early markers for future system and project performance. Ultimately, using results from a variety of projects related to different systems, it would be possible to identify the best practices for creating and managing engineering changes.

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Contact: Afreen Siddiqi
Massachusetts Institute of Technology
Engineering Systems Division
Cambridge, MA, 02139
USA
Tel: Int +1 617 253 2522
Email: Siddiqi@mit.edu
URL: http://esd.mit.edu/people/scholars/siddiqi/siddiqi.htm

Dr. Afreen Siddiqi is a Research Scientist in the Engineering Systems Division at the Massachusetts Institute of Technology. Afreen's research expertise is in modeling complex socio-technical systems. She is particularly interested in investigating the couplings and interactions between traditionally independent areas that now increasingly need to be integrated in future systems for efficient planning, design, operation, and regulation. Her work has focused on modeling and analysis of system architecture, performance, management, and logistics of a wide range of complex systems.