A Posteriori Design Change Analysis for Complex Engineering Projects

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Engineering changes are an inherent part of the design and development process and can play an important role in driving the overall success of the system. This work seeks to create a multidimensional understanding of change activity in large systems that can help in improving future design and development efforts. This is achieved by a posteriori analysis of design changes. It is proposed that by constructing a temporal, spatial, and financial view of change activity within and across these dimensions, it becomes possible to gain useful insights regarding the system of study. Engineering change data from the design and development of a multiyear, multibillion dollar development project of an offshore oil and gas production system is used as a case study in this work. It is shown that the results from such an analysis can be used for identifying better design and management strategies (in similar systems and projects) and for targeting design improvement in identified subsystems. The isolation and identification of change hotspots can be helpful in uncovering potential systemic design issues that may be prevalent. Similarly, strategic engineering and management decisions can be made if the major cost drivers are known.
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1 Introduction

Changes are part and parcel of most design and development processes of engineering systems. Once an initial design of a component, subsystem, or system has been finalized, it is very likely that it may undergo modifications or changes due to a variety of factors. The change inducing factors include original errors [1], new or changed customer requirements, or new or changed external conditions, such as market shifts [2,3]. In large, complex systems, understanding, and managing engineering changes well can be crucial. For firms engaged in design and development of large systems, understanding the change activity can be an important means for identifying areas of improvement. Analysis of change data can provide insights on overall change generation patterns in time (which can serve to characterize different designs and projects), change hotspots, (i.e., areas or subsystems that give rise to or undergo most changes) and cost drivers (areas that contribute most to change costs). These insights can help to improve the future designs of similar systems by potentially directing more attention and focus to change "hotspot" areas, allowing for strategically adjusting the change process by assessing and reviewing changes more carefully in costly areas/subsystems.

We propose that by investigating the larger engineering design change process (considered as one that embodies the individual change activities as a whole), one may elicit useful information regarding both system design and project management. While change activity is usually recorded and documented in large engineering efforts, it is usually done so for design configuration control and management purposes. The aggregate properties of the collection of changes are typically not analyzed and each change is treated individually. For large complex engineering systems, an understanding and characterization of their "meta-change process" (comprehensive), however, is invaluable. While the characterization can be done in a number of ways, we propose a simple, three-dimensional view of the collective change activity as a starting point. The three dimensions are time, change originating subsystem, and cost. Constructing a temporal, spatial, and financial view to analyze change activity provides useful system insights. The results can be used for identifying better design and management strategies and for targeting design improvement in identified subsystems. The isolation and identification of change hotspots can be helpful in uncovering potential systemic design issues that may be prevalent. Similarly, strategic engineering and management decisions can be made if the major cost drivers are known.

The time, space, and cost dimensions are chosen because they are among the most fundamental. There are many other attributes, however, that are needed to more fully define and characterize the engineering change process. For instance, an important dimension is the social dimension, i.e., the engineers and managers who initiate, process, and implement the changes. Similarly, the causes of change (errors, new requirements, market dynamics, etc.) are an important aspect to consider when studying the change process. In this work, we only focus on the basic dimensions of time, space, and cost. This provides a useful starting point for constructing an initial understanding of change activity that can provide relevant information for potential design and management improvements. Furthermore, there is a large variation in the way firms record and store engineering change data. Time (date of change), change area (location), and cost usually tend to be the most commonly recorded information. It is therefore useful to use these as the first basis for analyzing change activity.

1.1 Literature Review. The engineering design process has been the subject of active study [4] with focus ranging from (relatively) simple products [1,5] to large, capital intensive, and complex systems [6,7]. Within that context, the design iteration process, has been rigorously studied, experimented [8,9], modeled, and analyzed. In general, iterations are the repeated cycles of design activities in which engineers work between and among different teams (each working on a potentially different subsystem), till a feasible or optimized design that satisfies the given requirements is obtained [10]. In some cases, design iterations have been considered more broadly by including design modifications for new versions of a previous design (e.g., new models of automobiles based on yearly market trends) [8].

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While the product development process in general, and design iteration aspects in particular, have been widely studied, the topics of "design change" and "design change management" have received comparatively less attention. Furthermore, while it has been recognized from a management perspective that product development schedule, cost, and quality are driven by change and rework activity to a large extent [11,12], change activity from a more detailed technical and engineering design perspective is less understood. Note, that a design change is considered to be a process in which a design that had been previously considered as finished or completed is revised. The revision or modification may be to correct prior mistakes, meet new requirements, etc. This is in contrast to the design iteration process that is typically searching for a feasible and perhaps optimal design solution for a particular set of requirements.

A design change can have important cost, schedule, and design change propagation effects. With growing complexity, scale, and interconnectedness of subsystems in large engineering systems, it has become increasingly important to understand, predict, and strategically manage design changes.

Past studies on design change in large engineered systems have focused on change patterns over time [13] and change prediction [14,15]. The overall motivation and emphasis in these studies has been to develop methodologies for determining the impact of a potential change a priori so that suitable decisions about its implementation can be made. Recent work has also focused on studying the patterns and dynamics of change propagation in complex systems [16] based on a posteriori data. By tracking parent-child and sibling relationships between engineering changes, it becomes possible to trace out the full interconnectivity of changes over the system's development cycle.

This study builds on some of this past work. It takes a descriptive view of analyzing change activity through patterns in time, locations, and costs data. Furthermore, it provides an empirical basis for some of these descriptions by using an actual engineering change dataset of a large project. The results are specific to the analyzed dataset. However, they form an initial basis for furthering our understanding and characterization of change behavior in similar large systems. This work also attempts to relate change patterns to those that are already understood and found in systems in other contexts in systems engineering literature. Using additional data sets from similar systems and development projects, these results will be validated or further improved for their general applicability.

The paper is organized as follows. Section 2 describes a general framework in which change analysis can be conducted to create a macroscopic, multidimensional understanding of change activity. The framework is then used in Sec. 3 for analyzing a change data set related to a multibillion dollar, multiyear, offshore oil and gas production system design, and development project. The results are discussed in Sec. 4 in the context of the project and also in terms of their applicability in general. The last section provides a discussion on future research.

2 A Multi-Dimensional View of Change

Changes that arise in the design and development process can be described through many different attributes. Some key descriptive attributes include the final approval state, which systems, subsystems, 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 impact on lifecycle costs (during operations and maintenance). Other important information includes the reason for initiating the change, the change owner (person who identifies or request the change), and so on. Figure 1 shows an object-process diagram (OPD) [17] 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.

There are several ways in which the larger change process can be studied. For example, one could focus on the subprocesses

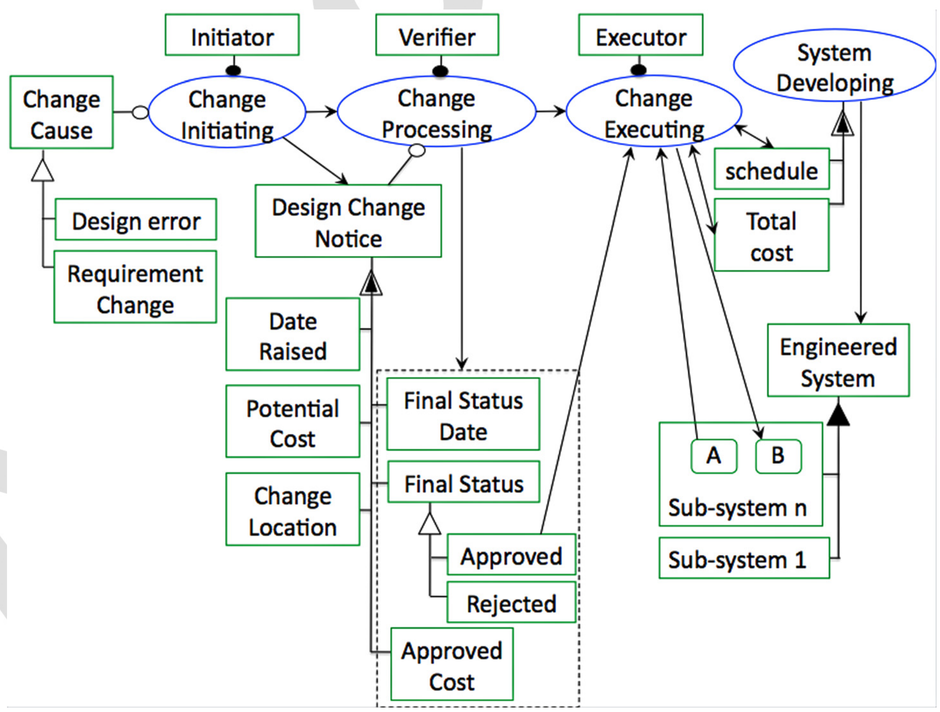

Fig. 1 An object-process diagram of design change

alone. Thus, one can analyze the mechanics and dynamics of the change initiation, verification, and implementation processes to identify improvement opportunities. Additionally, the management of the information, its documentation and flow can be assessed for potential improvements. In this study, we focus on the attributes of the change objects, i.e., change notices that are manifested as physical changes to the engineered system.

As mentioned earlier, while there are many potential attributes that can be analyzed, some of the most essential are that of time, space (change location or initiating subsystem), and cost. In this work the emphasis is on these three key aspects that collectively can provide important and relevant insights regarding the system design and development. Figure 2 shows these along three separate axes. It should be noted that for the actual case study that will be discussed in the next section, change location data was not available at the subsystem level. The "discipline" of the systems that were changed was used as a surrogate for location. This will be discussed in more detail in Sec. 3.

By framing engineering changes in this manner, it becomes possible to do a systematic analysis of change data in order to construct meaningful knowledge of the underlying system. This is not typically done in engineering design projects, where changes are often issued and managed as isolated actions, but not as an overarching ensemble.

Using the three-dimensional basis [of Fig. 2(*a*)], there are six different ways for analyzing change data:

(1) A time-only (dimension A) analysis will involve constructing change activity profiles over the project timeline. By determining the number of changes that arise per unit of time, it will be possible to characterize the change time profile that can be helpful in providing high-level understanding of the evolution and dynamics of changes.
(2) A location-only (dimension B) analysis in which the number of changes from each specific subsystem are tallied to allow for identifying the hotspots, i.e., the subsystems that gave rise to most change requests. Isolating hotspots can be important for informing future design decisions.
(3) A cost-only (dimension C) analysis will involve constructing histograms or frequency plots to identify the nature of change cost distributions.
(4) In a time-location (dimensions A-B) analysis, the number of changes from each initiator can be split up in some aggregate units of time (e.g., monthly or yearly basis). This allows for identifying "time-based" hotspots. There maybe some "early bloomers," i.e., subsystems that show a lot of change activity early in time and then settle down. Alternatively, there maybe late bloomers that initially do not generate changes but become active later on (which may then have cost implications for the project). There may be another class of subsystems that show no concentration of change activity in time and have a steady, uniform stream of changes throughout. This collective information can also potentially be used to inform rules for "design freeze" of future similar systems to be developed by the firm [18].
(5) For a location-cost basis (dimensions B-C), the change costs from each different initiator location are tallied up. This process allows for then isolating the cost drivers, i.e., subsystems that contributed most to the change costs. Due to the nature of different subsystems, it may be likely that the hotspots (subsystems with highest volume of number of changes) are not necessarily the cost drivers as well. For a system where this may indeed be the case, this information can be crucial for engineering managers.
(6) In a time-cost basis (dimensions A-C), one can construct cumulative cost over time plots to see how the costs were incurred and to identify any useful patterns that may help in future fiscal management decisions.

In this paper, the change analysis framework is applied to an extensive dataset of a large design and implementation project. The overall process that was employed in conducting a systematic analysis of design change is summarized in Fig. 2(*b*).

A large set of design change notices (DCN) that had been generated over the course of the multiyear project were compiled in a

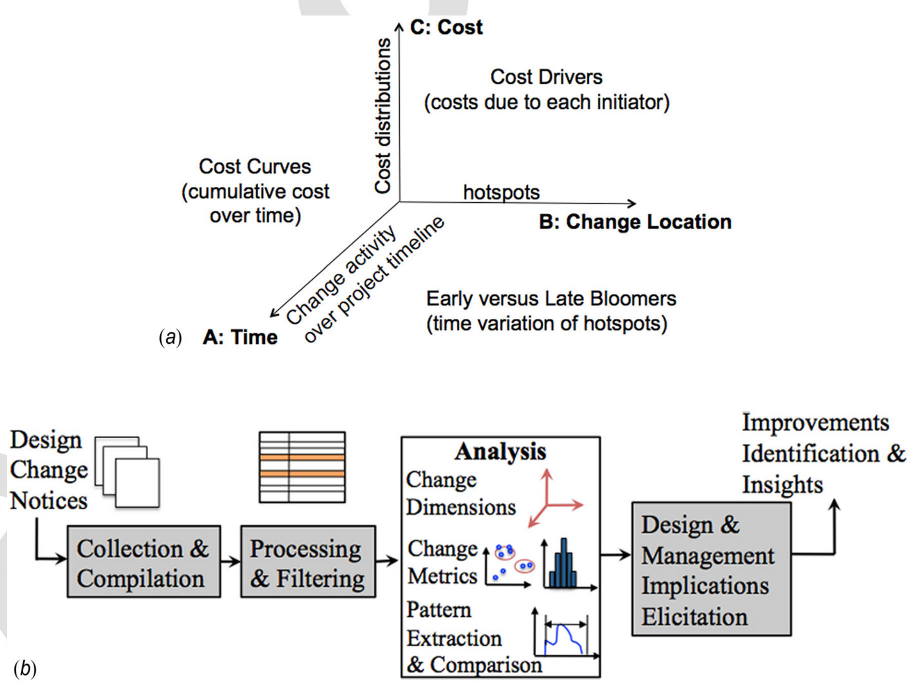

Fig. 2 (*a*) Dimensions of engineering change and (*b*) engineering design change analysis process

database. The data was subsequently processed with necessary filtering and amendments to allow for automated numerical analysis. The processed data was then analyzed along the various dimensions described above. It was also investigated using metrics that have been developed in prior work [19]. The empirical results were then compared, where applicable, with prior theoretical developments in system design literature. Furthermore, various patterns and trends that can have implications for improvements in future design and management of similar projects were elicited and identified.

3 Case Study: BP Angola Block 18 Greater Plutonio Project

The project data analyzed in this work relate to the BP Angola Block 18 Greater Plutonio development for oil and gas production. This offshore development area is located 16 km northwest of Luanda and is comprised of five fields in water depths varying from 1200 to 1450 m. The Greater Plutonio accumulation was discovered in 1999–2001. It was developed over 3.5 years and started oil production in October 2007. The initial capital expenditure (CAPEX) was approximately US $1 billion, and capital expenditure over the life of the fields is estimated at US $4 billion [16,20]. 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 a FPSO (floating, production, storage, and offloading vessel) for fluid processing and export. The FPSO is 310 m long with an oil storage capacity of 1.77×10^6 barrels and oil processing of up to 240,000 barrels per day (see Fig. 3) [16,20].

The scope of the Greater Plutonio project that was analyzed in this work was the design and build of the FPSO facility. Any design changes that were initiated and processed during this effort were recorded through design change notices. 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.), approved cost, change owner, etc.

All DCN information was compiled in a DCN excel register that had a total of 1147 records spanning 4 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 subsystems associated with the change, a higher-level categorization of "originating discipline" for which data were available for most records was used as a substitute for location information.

4 Data Analysis

The DCN register was analyzed to identify patterns in how changes were generated over time, what were the sources and impacts of change costs, and to detect the presence of any high change activity areas or "hotspots". The following sections describe the systematic assessment that was carried out using the general framework described in Sec. 2.

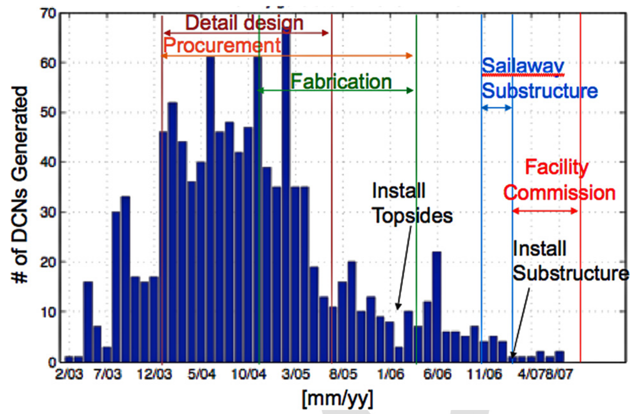

Fig. 4 Monthly change generation activity

It is important to note that—although this analysis focuses on cost, time, and change location—these dimensions are not the only drivers for change activity. Considerations such as safety, constructability, and operability are not investigated in this study, but will greatly influence the distribution of change activity in any oil and gas project.

4.1 Dimension A—Time Analysis. Figure 4 shows how the design changes were generated on a monthly basis over 4 years of the project. The key phases of the project such as detailed design, fabrication, etc., have also been marked.

The overall shape of the plot resembles the "ripple" pattern that has been studied and discussed theoretically in change analysis literature [13]. Figure 5 shows the different types of patterns that can arise in complex engineering systems.

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." [13]. Figure 4 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. This is an overall good indicator (for the project) since design changes later on can get expensive. Nonetheless, it is worth noting that the change activity does not completely die off after the detailed design stage. The DCNs continue well into the fabrication stage. It is interesting to see that there is a spurt of change activity

Fig. 3 FPSO vessel in Angola, Africa [6]

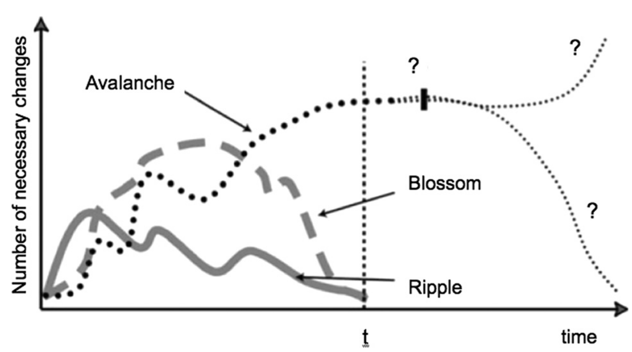

Fig. 5 Change effort and system behavior [25]

after the "Topsides installation" stage. A review of the change register indicates that many of these were related to telecommunications and electrical changes that are potentially easier to implement, once the topsides and hull have been mated. A key point of caution, however, is that the overall pattern can only be classified with certainty if the project target completion date (shown as "t" in Fig. 5) is known. The change activity has to be put in reference to that t, otherwise a ripple may really be a "blossom" with a long tail. For the project under study, the actual completion took 13% longer than originally planned. It is therefore, reasonable to consider the change activity as a ripple for this project.

4.1.1 DCN Approval Over Time. The DCN register used in this analysis provided information regarding the final status in terms of approval, rejection, or withdrawal of each change notice. These data were analyzed to see if there were any specific trends. On an aggregate level, out of a total of 1147 DCNs, 885 or 77% were approved. The rest of the DCNs were either rejected or withdrawn. This is a higher approval rate than what has been observed for radar system projects [19] but seems to be in line with other oil and gas projects of BP.

For a time-based analysis, the monthly rejection ratio (fraction of DCNs not approved) each month was plotted (shown in Fig. 6). It is interesting to note that there is a clear overall pattern. For most part of the project, the ratio is almost consistent at approximately 15%–20%. But toward the end of the project, the rejection ratio starts rising sharply (around January, 2006 once the topsides installation begins). In that phase of the project, it is reasonable to expect that changes would be resisted and will be difficult to implement. It should also be noted, however, that the total DCNs recorded for that time interval is also small (as can be seen in Fig. 4).

4.2 Dimension B: Change Location Analysis. In an ideal case, pertinent for informing future engineering design, change activity location at the subsystem level should be analyzed. The data available for this study, however, only provided information regarding the change originating discipline. There were a total of 22 different disciplines, listed in Table 1, associated with the 1147 DCN records. In order to determine areas of high change activity, these disciplines were used as a high-level substitute for quantifying the change frequencies on a location basis.

Figure 7 shows the number of approved DCNs for each discipline arranged in descending order. The first thing to note is that change activity is not uniformly spread across the different disciplines. There are some clear hotspots that consist of MR (marine), PR (process), and ME (mechanical). Hotspots are defined as subsystems that are subject to above average change activity. MR, PR, and ME form a top tier of high change originating areas. These three collectively account for 424 DCNs out of 885 approved DCNs. This means that ~48% or almost half of the changes originated from either marine, or process, or mechanical disciplines in this project.

Table 1 Change originating disciplines

AR	Architecture	MT	Material 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

Figure 7 also shows a second tier consisting of EL (electrical), PI (piping), ST (structural), and IN (iInstrumentation) that also stand out from the remaining areas in terms of total number of approved DCNs. This second tier has collectively 269 DCNs or 30% of the total. Overall, there are four tiers that can be identified. Each tier has similar levels of DCNs and there is a larger percentage difference in number of DCNs between two disciplines in different tiers than with those within the same tier. In tier 3, the collective contribution to change notices is 141 or 16%, while tier 4 contributes the remaining 6%. In summary, there are on the whole a few distinct classes in terms of number of DCNs into which all the disciplines can be grouped. The few disciplines that comprise the top tier dominate the change activity and are the change hotspots of the larger system. Classification of disciplines or subsystems into tiers has the potential to substantially improve change handling and personnel planning for resource allocation during design of future similar systems in the firm. A point of caution here is that for a more accurate assessment of change activity by discipline, the total contribution of each discipline to the design has to be factored in. The change notices should ideally be normalized with total designs in each discipline in order to obtain an unbiased view of change hotspots. In this dataset, only change activity information was available, therefore such a normalization was not made.

An integrated analysis of change notice frequency and approval rates was also performed. For this purpose, the change acceptance index (CAI) [19], defined as the ratio of total DCNs approved versus total DCNs raised for each discipline was computed. This CAI was plotted against the total number of DCNs raised for each discipline and is shown in Fig. 8.

It can be noted that change hotspots have approval rates close to the overall mean (of 77%). There are also some clear "change

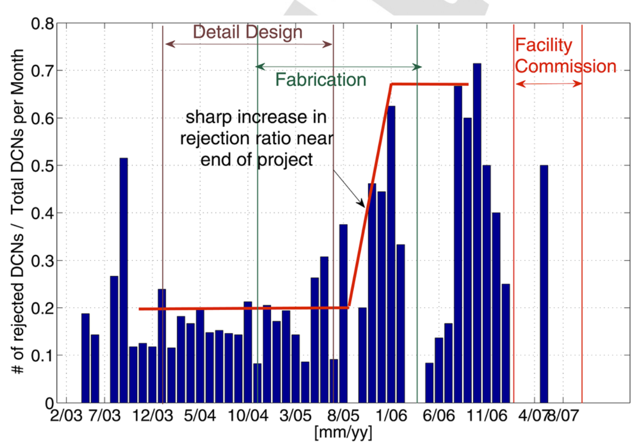

Fig. 6 Monthly DCN rejection ratio

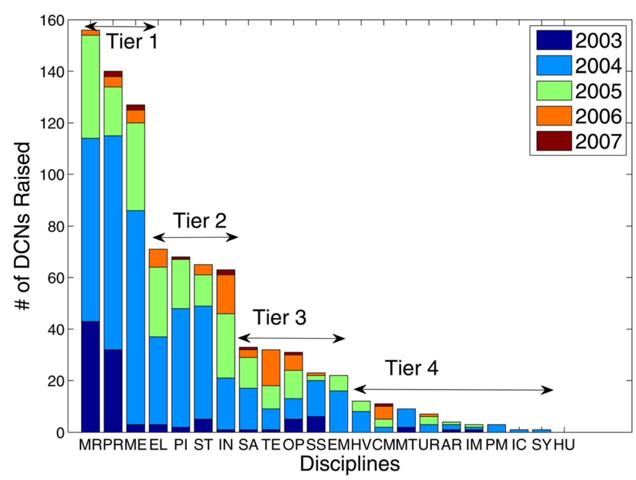

Fig. 7 Number of DCNs per discipline

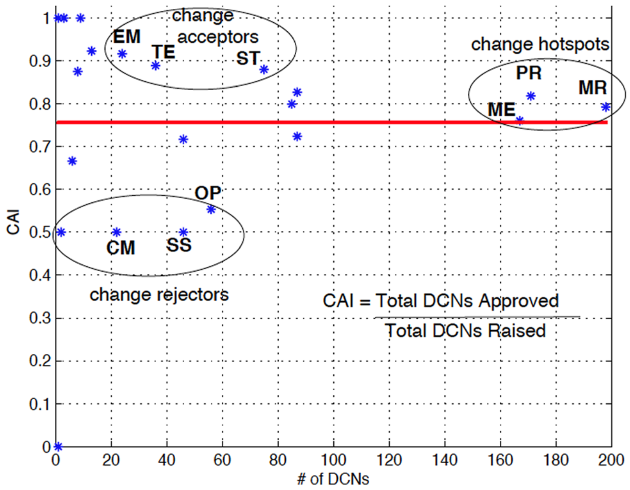

Fig. 8 Change acceptance index per discipline

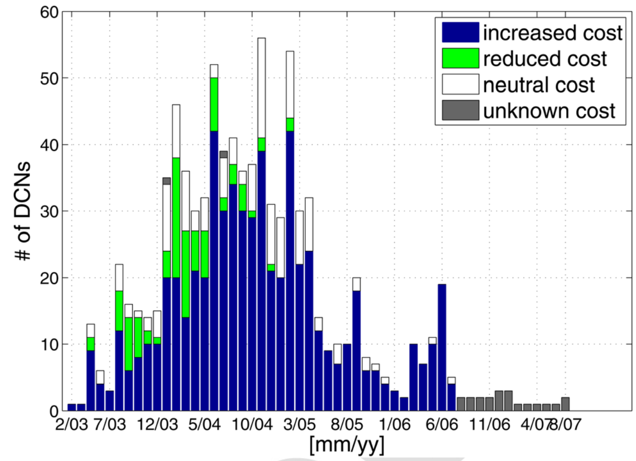

Fig. 9 Number of DCNs based on cost type

acceptors," i.e., disciplines whose change requests were almost always accepted. They have CAI of 10% or more than the average. These include EM (estimating), TE (telecomm), and ST (structural). Ideally, it would be interesting to know from a design standpoint if the change acceptors are also change absorbers, i.e., they accept change but do not propagate it forward to other systems (or disciplines in this case). Unfortunately, the dataset did not include explicit relationships between the DCNs, so it was not possible to determine if one DCN had given rise to another DCN.

Figure 8 also shows some clear change rejecters, i.e., disciplines whose CAI is 10% or more below the average. These include CM (commissioning), SS (subsea), and OP (operations).

In general, identifying the hotspots enables the engineers to carefully consider these areas in future designs keeping in view their nature of being prone to changes. Uncovering the cause of their higher change activity may also provide valuable information that may pertain to systemic design issues that can be improved. Similarly, knowing the acceptors and rejecters of change, can be useful for engineers and managers. Depending on the nature of the subsystem or area, one may formulate strategic design guidelines.

4.3 Dimension C: Cost Analysis. The cost data that are recorded for each DCN were of two types: potential cost and final approval cost. The potential cost was the cost estimate made at the time the change notice was filed. The final approval cost was the actual cost used as a basis for approving and authorizing the change. In some cases, the two were the same, while in many other DCNs, the potential and approved costs were not the same.

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). Figure 9 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 from Fig. 9 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. The total cost increase resulting from the approved DCNs was found to be 2.8 times the cost reduction effort. In total, the net change cost—from both cost increase and cost reduction changes—resulted in an approximate 3.5% cost increase of the total \$ 1×10^9 CAPEX.

The impact of cost on approval rates was also assessed to see if there was any relationship between the two. For this purpose, the potential cost, which was the estimated cost of the change at the time it was requested, of each DCN was analyzed in conjunction with the approval status. Of the 1147 records, potential cost data was available for only 571 DCNs (so the results need to be treated with caution). Table 2 summarizes the findings.

It is interesting to observe that while the approval ratio for DCNs that were to have a cost increase is 75%, it is 91% for cost reduction cases. Thus, it appears that if a cost saving DCN was proposed, there was a higher chance to be accepted, although in total, more cost increase changes were accepted and implemented than cost reduction changes.

Figure 10 shows the normalized approved cost increase and approved cost reduction distributions for approved DCNs. The normalization is based on average cost, computed as the simple ratio of net approved cost and total approved DCNs. The bins in the distribution are in multiples of this average cost. So for instance, the upper plot in Fig. 10 shows that there are 64 DCNs that have a cost increase ranging from 0 to 10% of the average cost and so on. It can be observed that the cost increase case has a large range of variation in DCN costs. The range varies from small fractions of the average cost to a few changes that are 50 times the average DCN cost. The distribution thus has a long "tail" in that the largest cost increase DCNs are fewer while smaller cost DCNs are larger in number. This confirms the finding in Ref. 19 that very large changes are relatively infrequent compared to the smaller and more ubiquitous design changes. Specifically, change notices with approved costs of 10 times the average cost or more are only 4% of the DCNs with cost increases. This "long-tailed" shape of the distribution has interesting implications from a cost risk management [21] and generational design learning standpoint. The presence of few, yet very expensive, changes suggests that a significant impact on change costs can be realized if these kinds of changes can be mitigated early in future projects. A key issue to consider is that the changes should not only be managed from a cost perspective alone, but their impact on system performance and overall value delivery should also be taken into account.

Table 2 DCN approval rate for cost types

	Increase	Decrease	Neutral
Total DCNs	373	81	117
Approval ratio	75%	91%	56%
Total approved DCNs	280	74	66

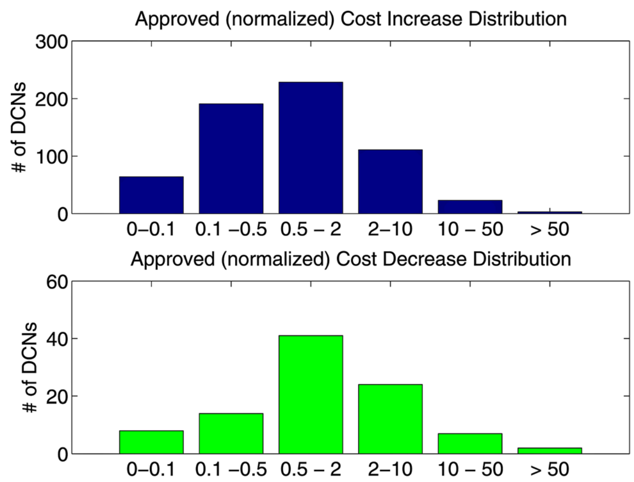

Fig. 10 Cost increase and reduction distributions

For cost reduction case, a long-tailed distribution is also observed. Furthermore, it can be seen that 27% of the DCNs provide estimated cost savings that are 50% or less than the average DCN cost. In these cases, the actual savings may have been eroded if one is to consider the costs of processing and handling change requests. The net result therefore may not have been significant in terms of cost reduction from these changes. The data suggest that there might have been opportunities in this project to significantly reduce change activity if limits were enforced on some required minimum amount of savings/monetary impact from the change. In general, one can conceive that cost saving change measures should be weighed against the costs of processing and managing those changes, in addition to considering their long-term, life-cycle impacts as well.

4.3.1 Cost Estimation. The DCN records were analyzed to determine the accuracy of the cost estimation process of the project. This was done by comparing the potential cost with the approved cost of each change notice. The comparison was made only for approved DCNs that had both potential cost and approved cost data provided. There were only 418 such records, therefore the results have to be treated with caution. Figure 11 shows how well the potential cost (estimated when a DCN was initially raised) compared against the approved cost. The relative normalized difference, i.e., (potential cost–approved cost)/potential cost has been plotted against the normalized approved cost for each DCN that was given approval. The normalization was based on the average DCN cost (as defined above in Sec. 4.3). The x-axis shows the approved cost in multiples of the average change cost. In the DCN database, cost increases for a proposed change were entered as positive values, while cost reduction changes were entered in as negative values. The negative approved costs (negative part of the x-axis) thus indicate cost reduction or savings.

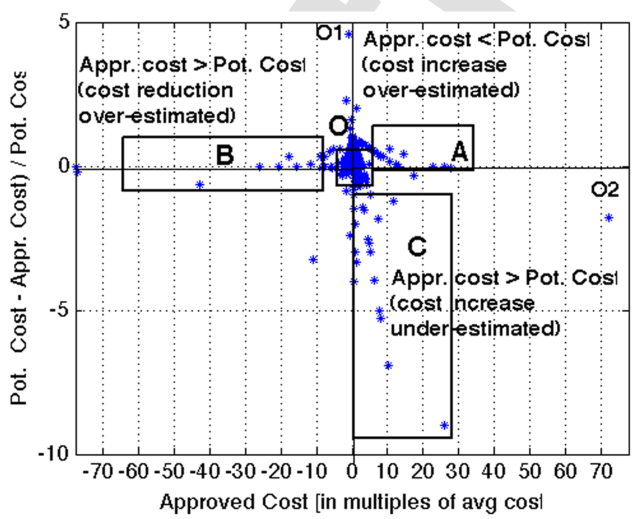

Fig. 11 Cost estimation comparison

The first observation that can be made from Fig. 11 is that most of the data are clustered within a box (labeled O) that is centered at the origin. It shows that relative cost difference is within $\pm 100\%$ for approved costs ranging from -5 to $+5$ times of the average cost on the x-axis).

There are also three distinct clusters, marked as A, B, and C on the Fig. 11. Cluster A corresponds to a set of DCNs for which the change cost was positive (the change incurred an additional cost as opposed to savings), however, the approved cost was less than the potential cost. For instance, consider a notional case in which the potential cost of the change is \$100 while approved cost for that change is \$80. A cost increase is incurred in the project (of \$80) but lower than what was originally estimated. In other words, the cost increase had been over-estimated. This means that initially the change seemed larger in terms of its impact than it ended up being at the point of approval. The more interesting clusters, however, are B and C. In cluster B, the data points correspond to DCNs for which there was a cost reduction (negative approved cost) and that reduction had been over-estimated. The points in cluster C indicate that there were DCNs with cost increases (therefore positive approved costs) that had approved costs much larger than the originally estimated potential costs (hence large negative value for relative cost difference). In other words, the cost increase had been grossly underestimated for these DCNs at the time these changes were initially proposed.

There are a few outliers in the plot. The two notable ones are labeled O1 and O2 (near the top end of the y-axis and near the right end of the x-axis, respectively). The O1 data point corresponds to a structural design change, although it is high on the y-axis (indicating a large difference in cost estimate), it is very close to the x-axis indicating that the approved cost was not very large. The O2 data point is more interesting since it shows a larger approved cost. It corresponds to a design change in which changes to a pumping architecture were made. This data point relates to the long tail in the cost increase distribution shown in Fig. 10.

In summary, it can be seen that for cost increase cases (right hand side of plot), there are DCNs with cost over-estimation as well as DCNs with cost under-estimation. However, cost under-estimation dominates in terms of magnitude. On the other hand, for cost reduction cases (left hand side of plot), most of the data are in the second quadrant indicating that cost savings were largely over-estimated (although the magnitude of the over-estimation was not too large). More specifically, it was found that on average, cost reduction was 11.6% less than initially estimated. Also, on average, the cost increase was 3.3% less than originally estimated. Thus, on the whole, it appears that estimates were almost correct when cost increases were to occur; however, cost reduction was over-estimated. This seems to be a bias, or inherent estimation error for cost reduction that shows an optimistic pattern in estimating costs for cost reduction changes. In future work, it will be explored whether such a bias is also present in other similar projects.

4.4 Dimension A-C: Time-Cost Analysis. In addition to the aggregate cost analysis, the data was analyzed in the cost-time domain as well. Figure 12 shows the cumulative net approved cost of approved DCNs. It is interesting to observe that this approximately resembles a "S" curve–flatter in the beginning and end and steeper in the middle. The S-curve is well understood in systems engineering, wherein it is known that a typical cumulative cost profile over time for a project follows an S shaped pattern. This

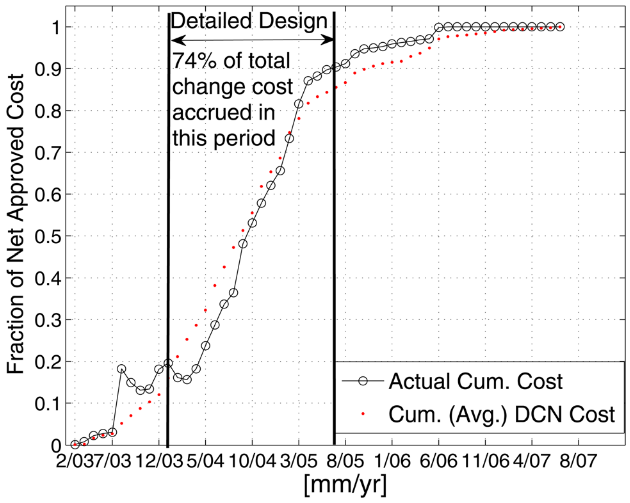

Fig. 12 Cumulative net cost over time

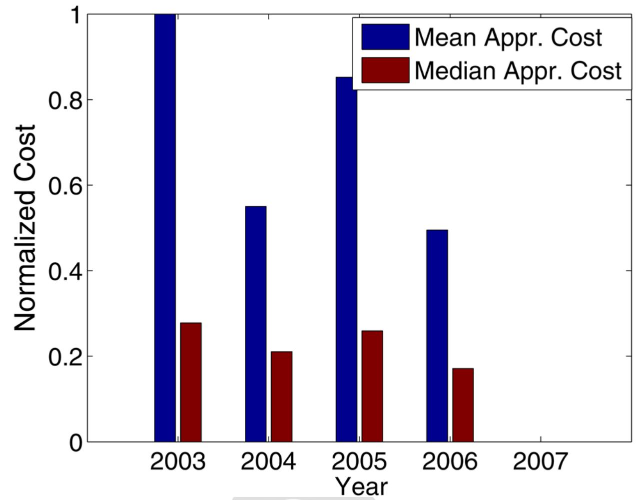

Fig. 13 Mean and median DCN cost per year

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 (and also many other phenomena such as technology innovation and adoption, population growth, etc.), this result empirically shows an "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.

Figure 12 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 2003–2004 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 management decisions. It should be noted that this S-curve relates to the ripple pattern of change activity in which the change effort starts, peaks, and eventually settles. For an avalanche case, in which the changes simply snowball out of control, the cost curve may look very different, possibly like an exponential curve.

In order to assess the influence of time on change costs, the mean and median costs of approved DCNs were also analyzed on a yearly basis (see Fig. 13). As was shown in Fig. 10, the cost data had a long tail; therefore, both mean and median values were computed. In long-tailed distributions, a few large values can unduly influence the mean, and the median is then a more appropriate measure to use. The mean and median costs were normalized with respect to the mean cost of the year 2003. In Fig. 13, there is no clear trend in the mean or median costs across the 4 years (approved cost data for 2007 was not available). The conventional wisdom holds that late changes are more costly. Based on that, an increasing trend going from 2003 to 2006 should have been present. However, this result shows the mean cost of a DCN to simply oscillate from year to year, while the median cost remains almost unaltered at approximately 25% of the 2003 mean cost. The trend in the data that shows a decreasing average cost in later project stages could be explained by the higher number of cheap changes towards the later stages. Furthermore, the cost is expected to increase with time for a given change. If a change is executed early in the project, it is likely to incur lower cost as compared to what it may incur if it were implemented later in the project. For clarification, Fig. 13 is the yearly cost data of different changes.

4.5 Dimension B-C: Location-Cost Analysis. In the context of the cost-location space, the relationship between change cost and the change originating discipline was investigated. The results are shown in Fig. 14 where the different cost types of increase, decrease, neutral (and in some cases unknown) are tabulated for each discipline arranged in alphabetical order. The top disciplines in terms of total number of DCNs (the hotspots) of MR, PR, and ME show the largest share of cost reducing DCNs as compared to others. In fact the relative ratio of cost increase, decrease, and neutral impact DCNs in these three disciplines is almost the same. There are some disciplines that show no cost reduction effort [such as integrity management (IM), safety (SA), systems (SY), TE, umbilical and risers (UR)].

This plot provides high-level information regarding cost behaviors of change activity in each discipline. For instance, in PI which is a tier 2 discipline in terms of number of DCNs raised, more than half of the change activity is either related to cost reduction or has neutral impact. Thus, while PI sees a lot of change activity, its cost impact is minor.

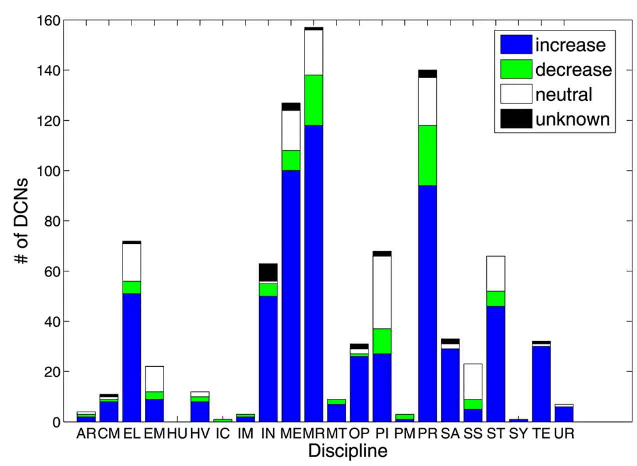

Fig. 14 DCN cost type per discipline

Figure 15 shows the cost impact in monetary terms for each discipline. The first plot shows the fraction of change cost increase contributed by each discipline. The second plot shows the fraction of change cost reduction, and the last plot shows the fraction of net cost due to each discipline. The disciplines have been arranged in descending order in terms of net cost. The highest net cost comes from marine, process and mechanical. These are the top tier disciplines shown in Fig. 7. Interestingly, the rest of the ranking is not the same. The fourth, fifth, and sixth highest net cost disciplines are ST, IN, and TE (in Fig. 15), whereas the tier 2 disciplines are EL, PI, and ST (in Fig. 7). Also, the clear tiered, stepwise grouping that was present in Fig. 7 (showing number of DCNs per discipline) is not present in the net cost case.

The key result is that the top disciplines in terms of DCNs also correspond to the highest cost, but the total ordering in terms of number of DCNs does not necessarily corresponds with that of cost. Some disciplines are more costly inherently on a per change basis. So simply, the number of changes alone is not the sole indicator of the costs that may be incurred due to a particular discipline. In order to illustrate this, Fig. 16 shows the mean, 5% trim mean and median costs of each discipline. The 5% trim mean is used here as a measure to counteract against the long-tailed cost distributions that were discussed earlier. In the 5% trim mean, the highest 5% and lowest 5% values are taken out of consideration when computing the mean. This is a standard statistical measure used for data sets where there are outliers present that influence the mean [22].

The costs have been normalized with respect to the mean values for the AR (architecture) discipline that had the highest mean cost. It is clear to see that there is indeed a difference in cost on a per DCN basis for each discipline. Figure 15 showed the total cost for a discipline, where as Fig. 16 shows the mean and median costs of a typical DCN for each discipline. In terms of mean, the most expensive disciplines seem to be AR, SY (systems), and UR. In terms of median costs, SY, AR, and MT (material engineering) are the highest. Since the mean/median costs are different, it is easy to see that the ranking of disciplines based on total cost will not necessarily correspond with that based on number of highest changes. It should also be appreciated that there are large differences between the mean and median costs for some disciplines (e.g., in AR, MR, etc.), indicating large variation in change costs within those disciplines.

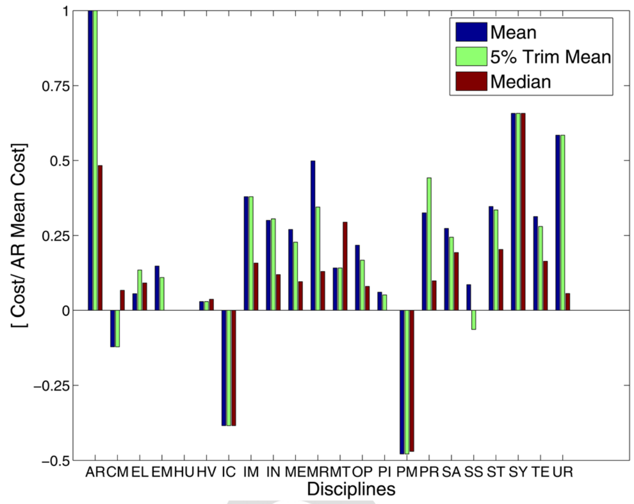

Fig. 16 Variation of DCN cost by discipline

4.6 Dimension A-B: Time-Location Analysis. The impact of time was assessed to see if the disciplines with the highest DCNs varied over time. Figure 7 provides this information. It can be observed that most disciplines have most changes in the beginning of the project (years 2003–2004 in light and dark blue), while some have a fair percentage of their total changes well into the later part of the project (2006–2007 in orange and brown) 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 2003–2004 period, MR, PR, and 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 2006–2007, TE, IN, EL, and OP dominate in terms of most changes. These can be thought of

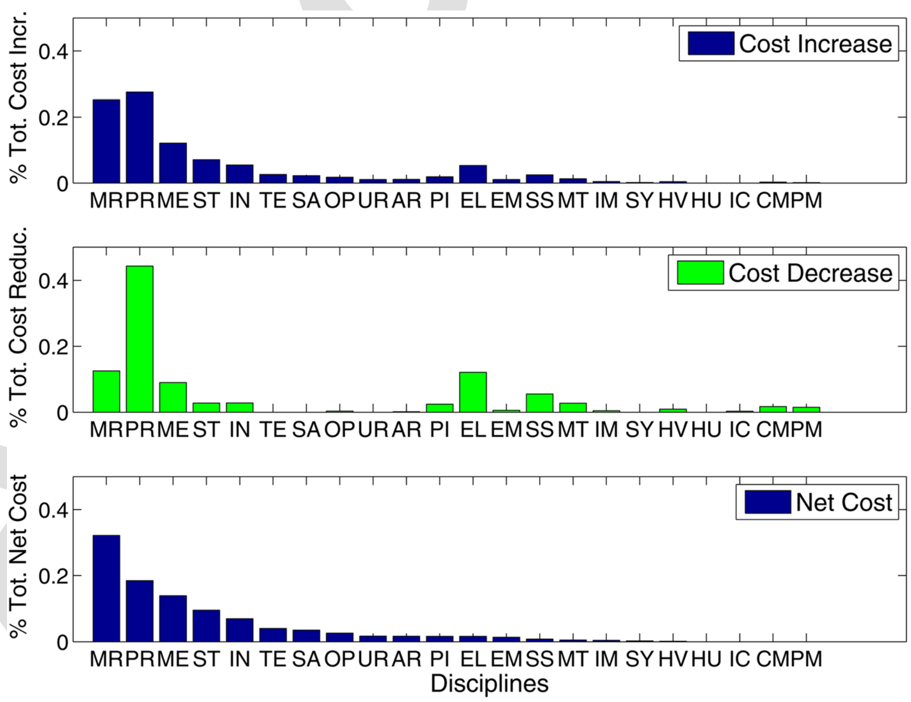

Fig. 15 DCN cost per discipline

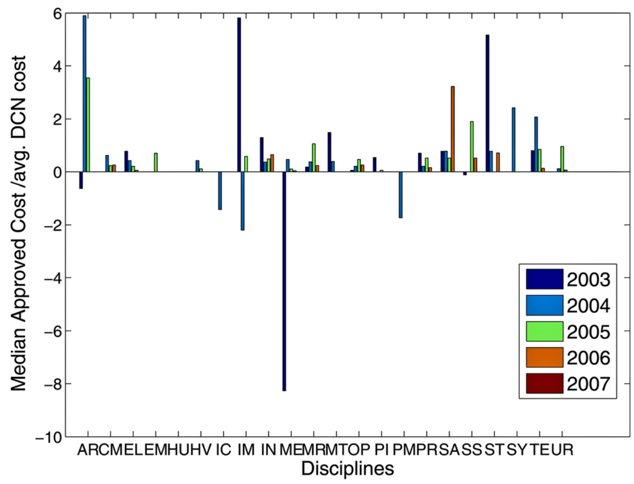

Fig. 17 Mean and median DCN cost per year

as the "late bloomers" that show up for changes late in the project. It is instructive to see however, that simply because a change is late does not mean that it will necessary incur more cost. The late changes here belong to a certain set of disciplines that perhaps due to their nature show up in the later stages. For instance, the telecommunication, instrumentation, and electrical by nature are such disciplines in which late changes are more likely to occur and may not necessarily be expensive to implement.

4.7 Dimensions ABC: Time-Cost-Location. For an integrated view of discipline, cost, and time, the median approved cost for each discipline in each year was plotted. The purpose was to identify any trends in cost over time on a discipline basis. Figure 17 shows the results. Based on the notion that cost of changes increase with time (as the project progresses), there should have been increasing trends of the median cost year over year. Figure 17, however, shows no such trend (there is no increasing progression of colors from blue to brown for each discipline). In fact, in many cases, it shows the opposite trend (in which the median costs go down over the years) such as in IN, SS, and ST.

It is important to consider that while the data show no apparent cost increasing trends with time, it is likely that in later years no cost saving changes were implemented. The fewer number of expensive late design changes also shows that toward the end of the project, the design had reached maturity, with only little need for change.

5 Conclusions and Future Work

This study provides a temporal, spatial, and resource centric view of change patterns in the design and development of a complex engineering system. It develops a systematic process and set of analyses to construct a system-level understanding of the collective change activity that occurs in a complex system. These analyses can be technically useful for improving future designs and can be strategically relevant for informing planning decisions for similar projects. Some of the benefits include:

- By classifying various projects based on their change activity profile over time, a firm can develop an understanding of how engineering changes impact overall project actual finish times (i.e. schedule), and also long-term performance (productivity, operational, maintenance costs, etc.) This can be useful for directing its future improvement strategies for both system design and project implementation.
- By isolating hotspots of change across different projects of similar systems, a firm can identify systemic design issues in general and areas of design improvements in particular. By knowing which areas are prone to changes, the firm can develop strategic design guidelines for improving future designs. For instance, in the presented case studied of an FPSO vessel design project, the top hotspots (or tier-1) disciplines were found to be marine, process, and mechanical that collectively accounted for 48% of the DCNs (Fig. 7) and 65% of the change costs (Fig. 15). A targeted upfront focus in design improvement and coordination in these disciplines can potentially yield large improvements in down-stream change activity. It should be noted that a more accurate measure for determining change hotspots due to potential systemic design issues would be one that accounts for change activity on a relative basis. In other words, total number of part designs for each discipline should be used to normalize the change activity of each discipline. Total design information was not available for this normalization to be made in the present analysis. It would however be important and in fact necessary in actual implementation of this approach.
- 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.
- The cross-dimensional views of how hotspots vary with time, and how change costs typically accrue, can help in resource allocation, planning, and budgeting. For instance, 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.
- Knowing which subsystems are change cost drivers can help in strategically and carefully handling their changes. In the case study presented here, it was found that changes in architecture, systems, and umbilical and risers were the most costly on a per DCN basis (Fig. 16). Changes in these disciplines (if this pattern is found to hold true in other projects of the firm) can be targeted for more carefully scrutiny and assessment and weighed against overall value and system performance.
- In this work a large data set of 1147 records was used as an empirical basis for formulating and illustrating how an initial descriptive understanding of change activity may be constructed for a system. It should be noted that actual design change data for large engineering projects has not been commonly published. The details of the data and its analysis should therefore serve as useful information for other studies on engineering design change.

The specific results of the case study were also interesting, since they confirmed and also refuted some common beliefs about engineering change. It was found that while change activity continued well into late stages of the project, the median change costs did not increase with time (which is perhaps a mark of a well-behaved project). It is important to note however, that any change propagation effects (if present) were not included in the analysis that can potentially impact how total change costs get assessed. In the design change notice recording system that was used in this study, specific information of how a requested change was linked to a prior request was not captured. Consequently, it was difficult to link various DCNs and elicit propagation chains or cascading effects.

Another important issue in patterns of engineering design change is the architectural and design maturity of the system under study. It can be expected that the patterns can be very different if the system design is "new" and original or if it is a variant [23] of a well-established and mature platform. The particular system studied in this work (an FPSO vessel) was a custom design. In oil and gas production systems, customized, rather than standardized, design has typically been the norm. There are, however, now increasing efforts towards commonality and standardization in that sector [24]. In future work, this analysis will be expanded to look at change activity and patterns in a different set of oil and gas production projects in which varying levels of standardization was implemented. Additional data sets from similar systems and projects will be used to validate or further refine the characterizations of change patterns that were made in the context of time, cost, and change location.

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. Additionally, 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 [25]. 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.

Another important extension to this work will be to include the social dimension of change activity. As mentioned briefly in Sec. 1, the social layer—the people who initiate, approve, and implement changes—is an important piece towards building a holistic and thorough understanding of design change. Indeed it can be argued that the dimensions of time, space and cost that have been considered here are in reality consequences of actions that stem from the human dimension—e.g., customers who may change requirements, designers who may overlook downstream feasibility, and managers who may alter plans. The knowledge, skill, experience, and even personal working styles can have significant impact on the end design and any consequent change activity. The human-factor in understanding design change is an important one to consider and will be incorporated in future expansion of this framework.

References

[1] Roser, C., Kazmer, D., and Rinderle, J. 2003, "An Economic Design Change Method," J. Mech. Des., **125**, pp. 233–239.

[2] Eckert, C., Clarkson, J., de Weck, O. L., Keller, R., 2009, "Engineering Change: Drivers, Sources and Approaches in Industry," International Conference on Engineering Design, ICED'09, Stanford, California, pp. 24–27 August, Paper No. 171.

[3] Fricke, E., and Schulz, A. P., 2005, "Design for Changeability (DfC): Principles To Enable Changes in Systems Throughout Their Entire Lifecycle," Syst. Eng., **8**(4), pp. 342–359.

[4] Jarratt, T. A. W., Eckert, C. M., Caldwell, N. H. M., and Clarkson, P. J., 2011, "Engineering Change: An Overview and Perspectives on Literature," Res. Eng. Des., **22**, pp. 103–124.

[5] K. T., and Eppinger, S. D., 2008, Product Design and Development, 4th ed, McGraw-Hill, New York.

[6] Steward, V., 1981, "The Design Structure System: A Method for Managing the Design of Complex Systems," IEEE Trans. Eng. Manage., **28**, pp. 71–74. AQ6

[7] Braha, D, and Bar-Yam, Y., 2007, "The Statistical Mechanics of Complex Product Development: Empirical and Analytical Results," Manage. Sci., **53**(7), pp. 1127–1145.

[8] Smith, R. P., and Tjandra, P., 1998, "Experimental Observation of Iteration in Engineering Design," Res. Eng. Des., **10**, pp. 107–117.

[9] URL http://www.ece.cmu.edu/~koopman/des_s99/electronic_electrical/bathtub.gif.

[10] Smith, R. P., and Eppinger, S. D., 1997, "Identifying Controlling Features of Engineering Design Iteration," Manage. Sci., **43**(3), pp. 276–293.

[11] Sterman, J. D., *Business Dynamics: Systems Thinking & Modeling for a Complex World* (McGraw-Hill, New York, 2000).

[12] Lyneis, J. M., Cooper, K. G., and Els, S. A., 2001, "Strategic Management of Complex projects: A Case Study Using System Dynamics," Syst. Dyn. Rev., **17**(3), pp. 237–260.

[13] Eckert, C., Clarkson, J. P., and Zanker, W., 2004, "Change and Customisation in Complex Engineering Domains," Res. Eng. Des., **15**, pp. 1–21.

[14] Lee, H., Seol, H., Sung, N., Hong, Y., and Park, Y., 2010, "An Analytic Network Process Approach to Measuring Design Change Impacts in Modular Products," J. Eng. Design, **21**(1), pp. 75–91.

[15] Clarkson, J. P., Simons, C., and Eckert, C., 2004, "Predicting Change Propagation in Complex Design," J. Mech. Des., **126**, pp.788–797.

[16] http://www.offshore-technology.com/projects/greater_plutonio/ (accessed: February 23, 2010).

[17] Dori, D., *Object-Process Methodology* (Springer-Verlag, ■, 2002). AQ7

[18] Turner, B., 1985, "Managing design in new product development process—Methods for company executives," Des. Stud., **6**(1), pp. 51–56.

[19] Giffin, M., de Weck, O., Bounova, G., Keller, R., Eckert, C., and Clarkson, P. J., 2009, "Change Propagation Analysis in Complex Technical Systems," J. Mech. Des., **131**, 081001 (2009).

[20] Production Begins at Greater Plutonio Press Release: October 2, 2007. (URL: http://www.bp.com/genericarticle.do?categoryId=2012968&contentId=7037042, Accessed February 23, 2010).

[21] Kossiakoff, A., and Sweet, W. N., *Systems Engineering: Principles and Practice* (John Wiley & Sons, New York, 2003).

[22] Devore, J. L. *Probability and Statistics for Engineering and the Sciences*, 2008, 7th ed.

[23] Martin, M. V., and Ishii, K., 2002, "Design for Variety: Developing Standardized and Modularized Product Platform Architectures," Res. Eng. Des., **123**, pp. 213–235.

[24] Setting the Standard," Frontiers - BP Magazine, 2005, No. 14, pp. 23–31.

[25] Systems Engineering Leading Indicators Guide, Version 2.0, January 2010, INCOSE Technical Product No: INCOSE-TP-2005-001-03.

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