A Bayesian approach to improving estimate to complete

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PROJECT: SHORT HISTORY

- Long term cooperation with Franco Caron (Management Engineering, Milan Polytechnic)

- M.Sc. dissertations with internship at the Italian largest oil and gas company
  - Alessandro Merli (now Project Manager at SIA S.p.A, ICT company providing services to financial institutions)
  - Cristian Borgarucci (now at Ariston Thermo Group)
  - Beatrice Pierini (now World Class Manufacturing Leader at Unilever)

PAPERS

- Caron, F., Merli, A. and Ruggeri, F. (2013), A Bayesian Approach to Improve Estimate at Completion in Earned Value Management. *Project Management Journal*, 44, 3-16.

- Caron, F., Ruggeri, F. and Borgarucci, C. (2013), Bayesian integration of internal and external views in forecasting project performance. *Journal of Modern Project Management*, 1, 112-121.

- Caron, F., Pierini, B. and Ruggeri, F. (2016), A Bayesian approach to improve estimates to complete. *International Journal of Project Management*, 34, 1687-1702.

SUMMARY OF THE WORK

- The capability to develop a reliable 'Estimate at Completion' from the earliest stage of project execution is essential in order to develop a proactive project management.
- This paper provides a methodology to support the development of the Estimate at Completion in large engineering projects.
- In order to accomplish this aim, a model to formulate estimates at completion is presented which integrates through a Bayesian approach three knowledge sources: experts' opinions, data from past projects and the current performance of the ongoing project.
- The model has been applied to three Oil and Gas projects in order to forecast their final duration and cost.
- These projects are characterized by a high level of size, uncertainty and complexity representing a challenging test for the model.

SUMMARY OF THE WORK

- The results obtained show a higher forecasting accuracy of the Bayesian model compared to the traditional Earned Value Management (EVM) methodology.

- Moreover, the estimates at completion calculated using the Bayesian model are not point estimates such as those calculated by EVM.

- In fact, the Bayesian approach leads to a probability density function for the forecasted final cost and duration.

- Hence, the project manager obtains an indication of the degree of confidence about the expected value forecasted which results in better quality information available for the decision making process.

INTRODUCTION

- Forecasting is a critical process in project management since, relying upon sound estimates to complete, the project manager can steer the ongoing project in order to meet specific time and cost objectives.

- Planning and forecasting are strictly intertwined both in the early stage of the project life cycle when the project baseline must be determined and then throughout the entire life cycle when effective decisions must be made.

- In an Earned Value Management context, the role of the Estimate to Complete (ETC), i.e. how much money and time is needed in order to complete the project, is critical, since the information drawn from the ETC is essential to identify suitable corrective actions in order to achieve the project objectives.

- This approach to project control corresponds to a feed-forward control loop, since analysis of the future informs present-day decisions.

INTRODUCTION

- At a given time in the project cycle, i.e. the time now (TN), a certain amount of the work has been completed (Work Completed, WC), while the rest of the work is still to be completed, corresponding to the Work Remaining (WR).

- The cost and time performance related to the WC is known, while a forecast has to be developed for the WR.

- It should be noted that both the accuracy of the forecast of WR and the impact of the corrective actions that may be implemented based on the forecast will depend on the progress of the project at the TN.

- The effectiveness of the corrective actions is greater in the early stages of the project execution and progressively diminishes as progress increases: in fact, as progress increases, the degrees of freedom available to steer the project tend to reduce progressively.

INTRODUCTION

- On the other hand, the capability to forecast the project final duration and cost follows an opposite trend. In fact, at an early stage in the execution phase, the knowledge available to the decision maker is scant and rapidly evolving; therefore, the capability to provide a reliable forecast is reduced, particularly if the forecast is only based upon the analysis of the performance of the ongoing project until the Time Now, without considering any other knowledge source.

- From a survey analyzing the data of more than 300 mega-projects, it appeared that in 2010 65% of the industrial projects with a minimum budget of 1 billion US dollars did not succeed in meeting the objectives of cost, duration and quality.

- Even though project management systems based on EVM have been extensively used in the recent years, failure to meet planned objectives is common, in particular in large engineering and construction projects such as in the oil and gas industry.

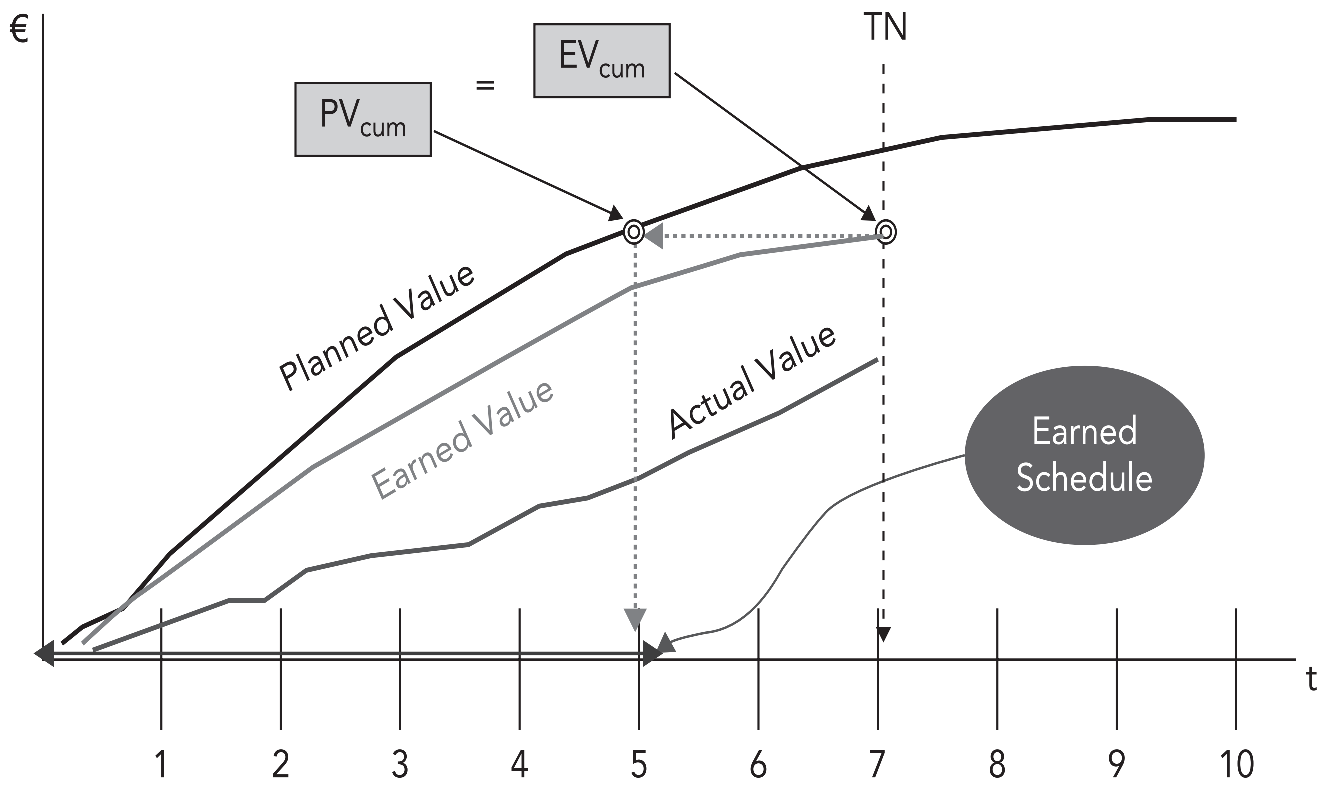
EARNED VALUE MANAGEMENT

- EVM is an efficient and synthetic performance measurement and reporting technique for estimating cost and time at completion.

- The basics of EVM are described by three curves
  - Planned Value (PV), the budgeted cost of work scheduled at TN (Time Now)
  - Earned Value (EV), the budgeted cost of work completed at TN
  - Actual Cost (AC), the actual cost of work completed at TN

- EVM was improved by Lipke (2003), who introduced the concept of Earned Schedule (ES) for measuring schedule performance in time units and overcoming the flaws associated with a schedule index defined as the ratio between EV and PV. Earned Schedule is the time at which the EV value achieved at TN should have been obtained according to the project baseline.

EARNED VALUE MANAGEMENT



PERFORMANCE INDICES

- Summarize project's past performance during WC
  - Cost Variance: $CV = EV - AC$
  - Schedule Variance: $SV(TN) = ES - TN$
- Extrapolate current trend and estimate future performance during WR
  - Cost Performance Index: $CPI = EV/AC$
  - Schedule Performance Index: $SPI(TN) = ES/TN$
- In the basic approach, the estimate of final cost (i.e. EAC) and final duration (i.e. TAC, Time at Completion) are based on the following:
  - $EAC = AC + (BAC - EV)/CPI_f$
    - BAC Budget at Completion
    - CPI_f Cost Performance Index estimated for WR
  - $TAC = TN + (SAC - ES)/SPI_f$
    - SAC Scheduled at Completion
    - SPI_f Schedule Performance Index estimated for WR

PERFORMANCE INDICES

- Here interest in Normalized Deviations at TN:
  - Normalized Deviation Cost: $ND(c)_{TN} = \frac{AC_{TN} - EV_{TN}}{EV_{TN}}$
  - Normalized Deviation Time: $ND(t)_{TN} = \frac{TN - ES_{TN}}{ES_{TN}}$
- and even more at TF (Final Time): parameters to be estimated
  - Normalized Deviation Cost at completion: $ND(c) = \frac{AC_{TF} - BAC}{BAC}$
  - Normalized Deviation Time at completion: $ND(t) = \frac{TF - SAC}{SAC}$

  where AC_{TF} and TF indicate the final actual cost and duration of the project, while BAC and SAC indicate the planned cost at completion and duration of the project, respectively.
- When a budget overrun is reported, ND is greater than zero, whereas if an under-run is recorded, ND is less than zero.

SOURCES OF KNOWLEDGE

- Different sources of knowledge
  - Explicit internal knowledge from work completed (WC): Normalized Deviation Cost $ND(c)_{TN}$ at Time Now
  - Tacit internal knowledge from experts' judgments about possible events affecting the project's work remaining (WR)
  - Explicit external knowledge about similar projects completed in the past
  - Tacit external knowledge about identification of similarities between current project and some past projects in order to use past data for the current project

SOURCES OF KNOWLEDGE

- Different uses of knowledge
  - Traditional EVM approach: utilizing only data records related to WC, by extrapolating the current performance trend into the future
  - Caron, Merli, F.R.: adjusting the trend resulting from data records through experts' judgments about the expected performance during WR
  - Caron, Pierini, F.R.: integrating the internal view of the project, i.e. data records related to WC and experts' judgment related to WR, with data records deriving from similar projects completed in the past

ESTIMATION OF INDICES AT COMPLETION

- Data: $ND(c)_{TN}$ at Time Now
- Quantity of interest: $ND(c)$ at completion
- Model: $ND(c)_{TN} = ND(c) + \sigma(TN)e$
  - $e \sim N(0,1)$
  - $\sigma(TN)$ standard deviation getting smaller and smaller when TN is approaching TF
- Simplifying notation: $x(t) = \mu + \sigma(t)e$
- Prior on μ: $\pi(\cdot) = \epsilon\pi_E(\cdot) + (1-\epsilon)\pi_S(\cdot)$
  - $\pi_E(\cdot)$: experts' opinion
  - $\pi_S(\cdot)$: similar projects
  - $\epsilon : 0 \leq \epsilon \leq 1$ weight of experts' opinion

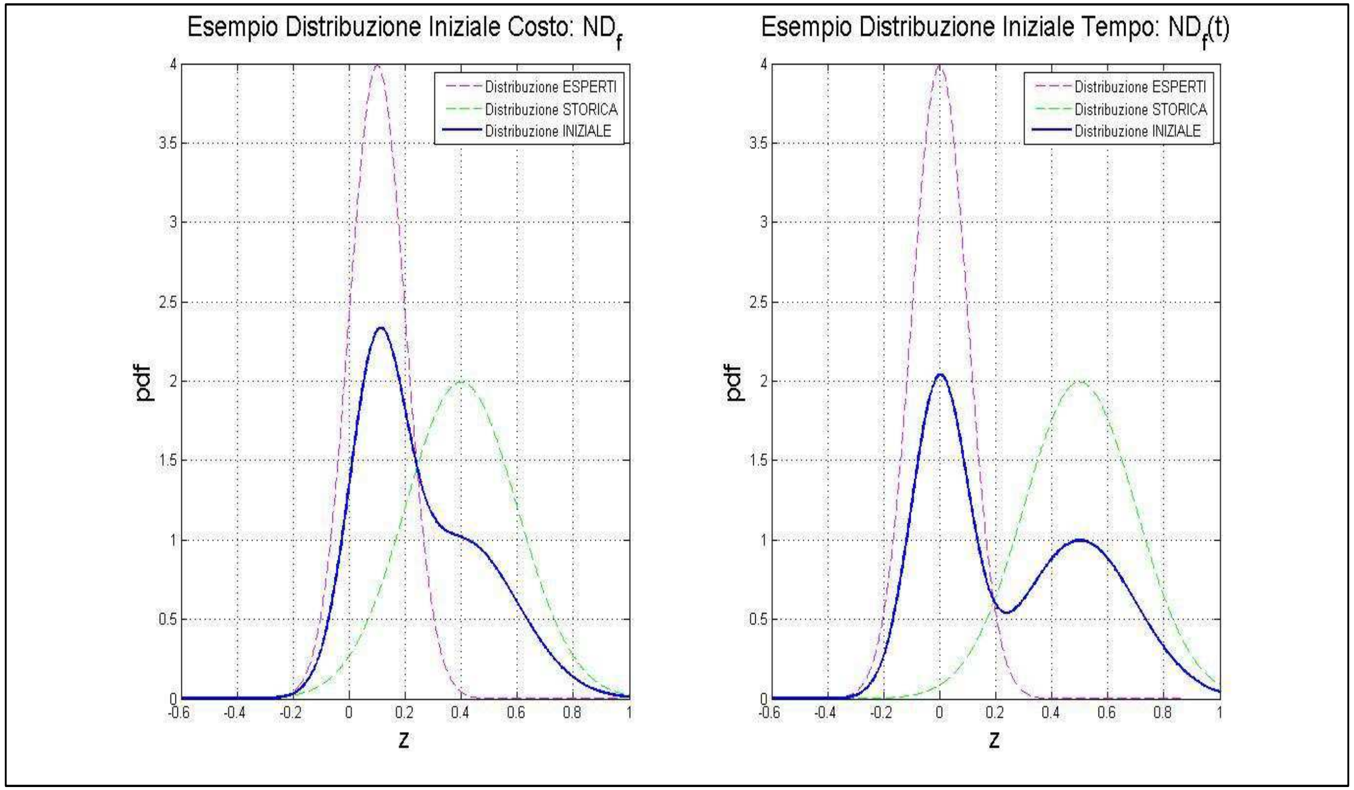
PRIOR FROM EXPERTS' OPINIONS

- Experts unable to provide quantitative judgements
- Qualitative judgements possible on pairwise comparison between indices being more or less likely in an interval than in another one
- $\Rightarrow$ Analytic Hierarchy Process (AHP) with all its pros and cons
- Experts too optimistic at the start of a project $\Rightarrow$ minor weight (ϵ) w.r.t. past projects
- No prior from past projects for completely new ones $\Rightarrow$ $\epsilon = 1$, i.e., just experts' opinions count
- Gaussian prior

PRIOR FROM SIMILAR PROJECTS

- Role of experts relevant since ...
- we consider only projects of same type ...
  - Italian oil and gas company: on shore, off shore and subsea
- ... sharing the traditional project features ...
  - size, technology, client, geographical area, etc.
- ... with a similar risk profile
  - risk quantity, risk type, risk exposure, etc.
- $\Rightarrow$ Gaussian prior $\pi_S(\cdot)$ with mean μ_S and standard deviation σ_S given by sample mean and standard deviation of past indices at completion

MIXTURE OF PRIOR DISTRIBUTIONS



STANDARD DEVIATION OF THE MODEL

Standard deviation $\sigma(t)$ chosen as a function of the progress of the project and the distances between indices at time now TN and expected indices (w.r.t. priors) at final time TF.

- Cost distance $\Delta_c = |ND(c)_{TN} E_P[ND(c)_{TF}]|$
- Time distance $\Delta_t = |ND(t)_{TN} E_P[ND(t)_{TF}]| \cdot SAC$

  (SAC Schedule at completion)

STANDARD DEVIATION OF THE MODEL

Progress and distance classes.

Low	Medium	High
Project Progress		
[0, 30%)	[30%,65%]	(65%,100%]
Δ_C		
[0,0.05]	(0.05,0.1]	>0.1
Δ_T		
[0, 3 months)	[3, 5 months)	$\geq$ 5 months

Standard deviation for the likelihood function.

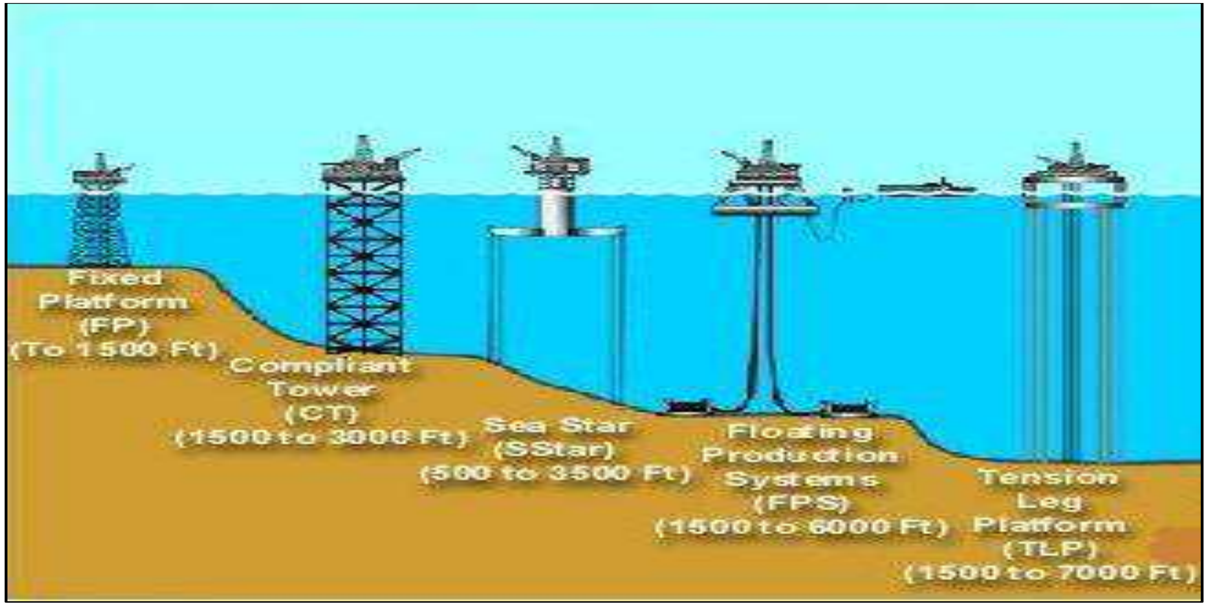
σ_{TN}		Distance		
		L	M	H
Project progress	L	0.35	0.45	0.55
	M	0.25	0.35	0.45
	H	0.15	0.25	0.35

CASE STUDY: OIL AND GAS COMPANY

- The research activity was developed in the years 2013-2014. The largest Italian company in the oil and gas industry was involved. In this industry, projects are very large, complex and uncertain, therefore the forecasting process is very critical.

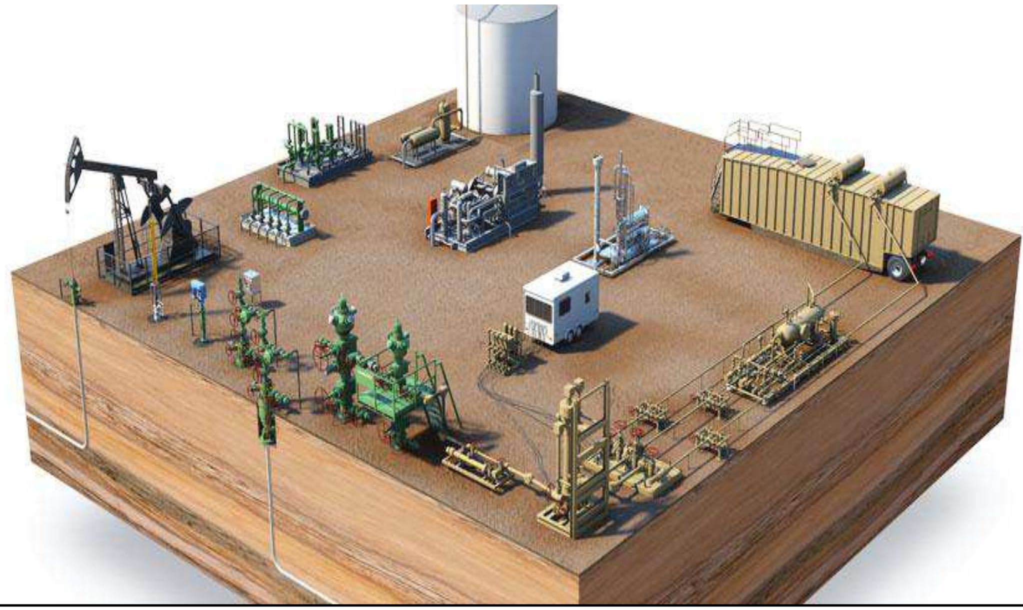
- Three types of projects have been identified:
  - offshore
  - onshore
  - subsea

CASE STUDY: OIL AND GAS COMPANY



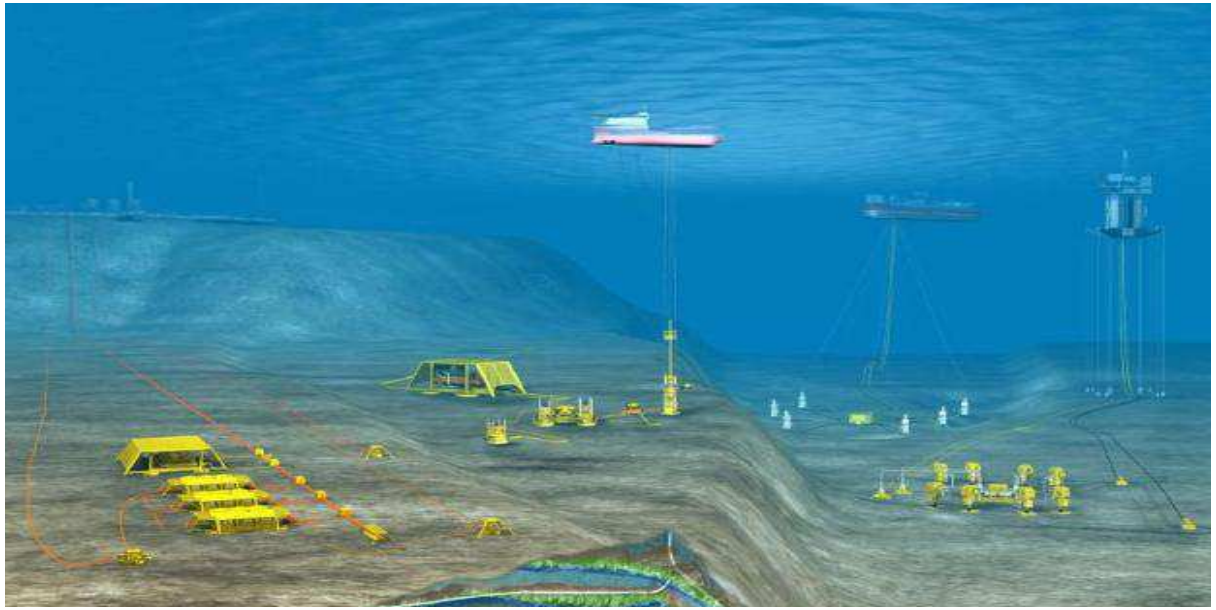
Offshore projects are denoted by offshore facilities for drilling and extracting hydrocarbons. Fixed or floating platforms can be used, depending on water depth. The extracted hydrocarbons are then transported onshore through a sea line-system

CASE STUDY: OIL AND GAS COMPANY



Onshore projects are characterized by the construction and installation of onshore facilities. The liquid and/or gas hydrocarbons extracted from the wells are firstly stored and then the liquids are sent through flow-lines to a preliminary treatment unit and then to a refinery. The gas follows a similar process until the preliminary treatment; afterwards it is sent for further treatment through a gas pipeline

CASE STUDY: OIL AND GAS COMPANY



Subsea projects are characterized by undersea facilities for extraction and production. The need to install undersea facilities is due to the technical or economical infeasibility of utilizing offshore platforms. When there are more than one undersea wells, the wells are interconnected through flow lines, in addition to the sea-lines that link the wells of extraction and production with onshore facilities

CASE STUDY: OIL AND GAS COMPANY

- Based on this classification, three clusters of about 6 to 8 projects completed in the past have been identified and used as classes of reference. For each cluster one of the most recent projects was chosen as ongoing project. At different times (Time Now) throughout the life cycle of the ongoing project the forecasting process was performed, based only on the information available at that Time Now, both in terms of data records and experts' judgment.

- Whilst data records were immediately available from the corporate information system, experts' judgments had to be collected through a set of interviews.

- The chosen interviewees were five project managers not directly involved in the three ongoing projects, each featuring a different level of professional experience.

- The interviews have been carried out using the same methodology, whilst a different weight has been assigned to each expert, based on the years of experience in the oil and gas industry.

CASE STUDY: OIL AND GAS COMPANY

- For each project, each interviewee was asked to simulate a forecasting process at each Time Now throughout the project life cycle, using only the available knowledge at the Time Now.

- The Analytic Hierarchy Process (AHP) was adopted as an eliciting approach, based on a set of pairwise comparison between the alternatives considered during the estimating process.

- A fixed interval approach was undertaken, considering 6 intervals (to keep the number of comparisons small at 15) in which the index of interest was more or less likely to be.

- For every pairwise comparison, the same question was asked to the interviewees, i.e.: "How probable is that the final time / budget deviation will fall in the first interval, respect to the second one?".

- The answers expressed in the natural language were then converted into numbers ranging from 1 to 9.

CASE STUDY: OIL AND GAS COMPANY

- After the elicitation round, the consistency of the values obtained from each expert was verified, using the measure of inconsistency $\frac{\lambda_{max}-n}{n-1}$, where n is the matrix size and λ_{max} the largest eigenvalue.

- If the measure of inconsistency is above 0.1, the matrix would definitely be considered inconsistent. In this case the software Expert Choice (or a MATLAB code in our case) could point out the intervals to be revised.

- Individual judgments were summarized into a group's matrix using the weighted geometric mean of the pairwise judgements, with weights based on the experience of each interviewee.

- Considering the normalized eigenvector associated with the largest eigenvalue, the final set of probability values assigned by the group of experts to each interval can be obtained.

- Gaussian distributions for budget overrun ND and completion delay ND(t) were chosen with mean and variance matching the ones computed for a random variable assigning the group interval probabilities to each middle point of the intervals.

CASE STUDY: OIL AND GAS COMPANY

- The Bayesian model has been applied to three projects, each of them belonging to one of the three types of project. The Offshore project will be named Project A, the Subsea one as Project B and the Onshore one as Project C.
- Here we will present just project A.
- The scope of project A consists of the installation of a fixed conventional platform 100 miles from the coast and in waters of 60 m depth. There are six wells to be drilled and a sea-pipeline has to be set up as well in order to connect the different wells to the platform.

CASE STUDY: OIL AND GAS COMPANY

- Basic data about Project A are defined in the next, where:
  - PP_{TN} stands for Planned Progress at Time Now, in agreement with the baseline;
  - AP_{TN} is the Actual Progress at Time Now, i.e. the physical actual progress reached by the project at Time Now.

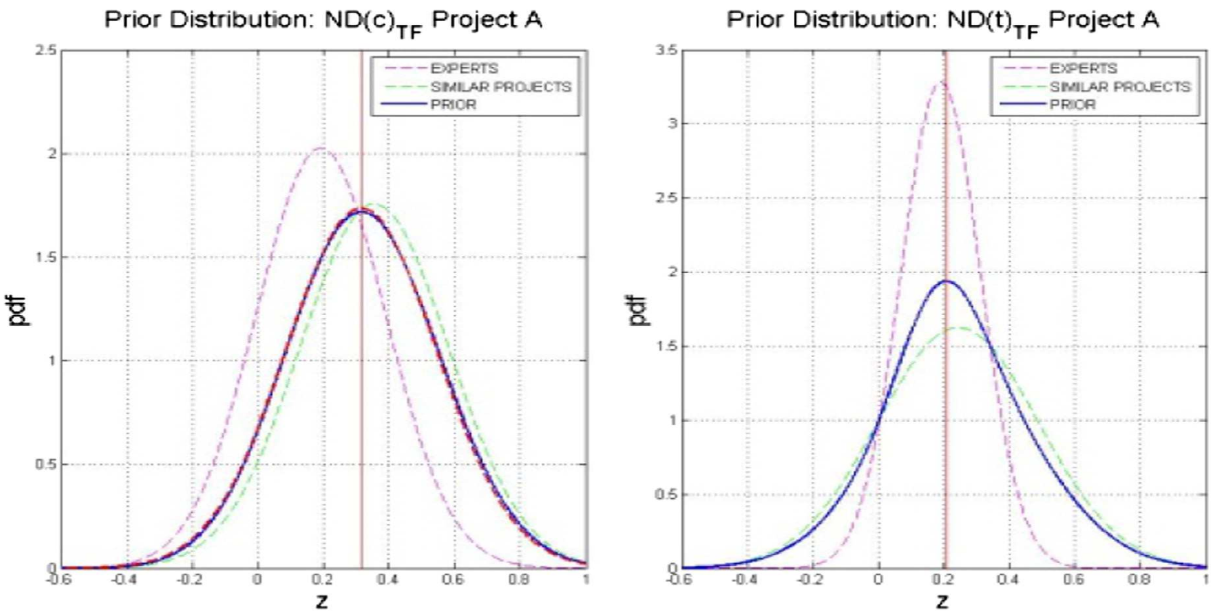
The first row in the Table, i.e. "New/Legacy Area", indicates whether the project is developed in a geographical area where the company has experience in operating or in a New Area. In the case of a New Area the degree of uncertainty of the project rises, since there is no established relationship with suppliers and subcontractors. In particular, the AP_{TN} of 36.45% is to be noted, since it will be useful to define the weights of the prior distribution and the standard deviation of the likelihood function.

CASE STUDY: OIL AND GAS COMPANY

Project A: offshore	
New/legacy area	Legacy area
BAC	231.26 MUSD
SAC	30 months
Time Now	Month 16
Planned data	
PV_{TN}	205.82 MUSD
PP_{TN}	51.13%
Actual data	
AC_{TN}	103.82 MUSD
AP_{TN}	36.45%
Earned value and earned schedule	
EV_{TN}	97.52 MUSD
ES_{TN}	13.56 months
Time Now performances	
$ND(c)_{TN}$	6.46%
$ND(t)_{TN}$	17.99%

CASE STUDY: OIL AND GAS COMPANY

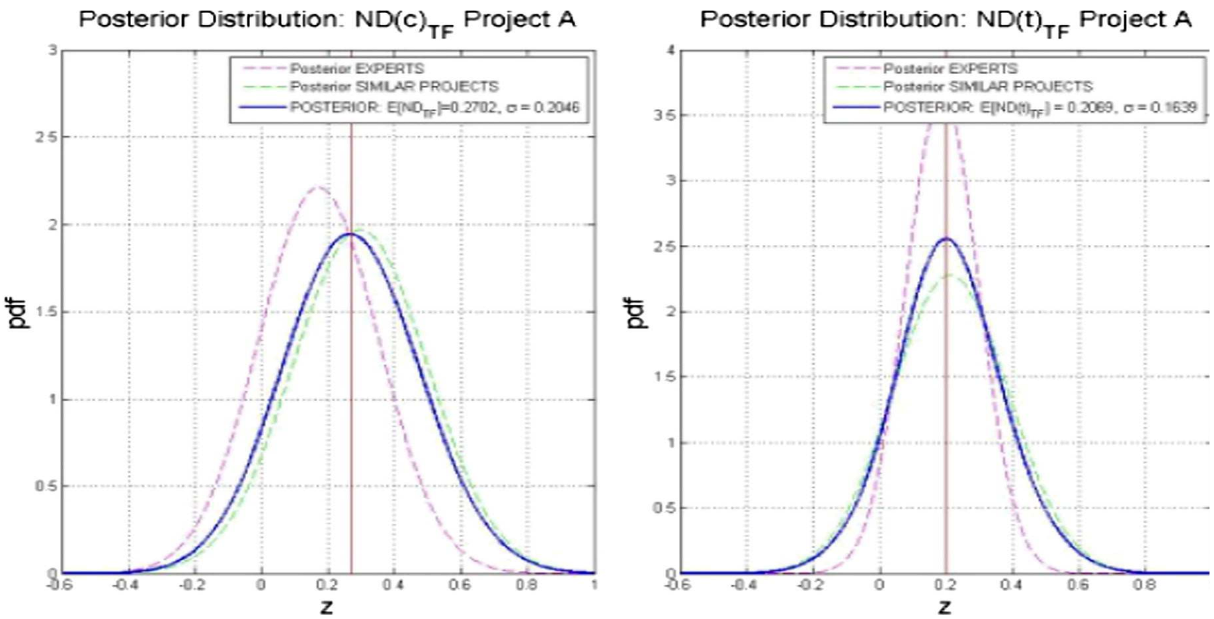
Prior distributions for final cost and time performance of Project A



Experts more optimistic than prior from the cluster of similar projects, both for time and cost final performance. The latter is more relevant since $\epsilon = 0.2$ because of the low physical progress reached at time now.

CASE STUDY: OIL AND GAS COMPANY

Posterior distributions for final cost and time performance of Project A



The posterior distribution of $ND(c)_{TF}$ shows a decrease w.r.t. the prior (whereas is very small for $ND(t)_{TF}$) with a reduction of the budget overrun.

CASE STUDY: OIL AND GAS COMPANY

MSE for Bayesian Model and EVM in the three oil and gas cases combined

Comparison of the mean squared error.

Mean squared error	Bayesian model	EVM
MSE cost	$1.23 \cdot 10^{-2}$	0.1683
MSE time	$9.3 \cdot 10^{-3}$	$3.55 \cdot 10^{-2}$

The Bayesian model is more accurate: its MSE is 10 times lower, both for cost and time performance, due to the larger amount of information used, even though the model was tested on very complex and risky projects.