Impact of engineering process on construction cost of HVDC offshore wind energy converter station: a system dynamics approach

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Abstract

A Norwegian based service company needed improved work performance with reduced cost of construction. Its recent internal study shows the engineering man-hours used in projects recently completed and on those near to their completions, have significantly increased compared to similar previous projects. This is of concern because the engineering processes are the cornerstones that all the company's activities are founded on. A multi-phase system dynamic model that represents the engineering process was built to assess impacts of work process, resource capacity, scope, and targets on project performance. Project performance is measured in cost, cycle time, and quality. The model was calibrated to DolWin Beta, an offshore wind energy project of the company. Sensitivity tests show cost and quality are more sensitive to work precedence relations. Comparison between simulated and historical records show the model replicates actual engineering work progress during most of the development period. The model was further applied to investigate schedule completion date policies for improved project performance. Follow up discussions with the company's managers revel this paper makes a practical contribution to the company's learning. A recently started project, which has been applying system dynamics principles, achieved a 0.9 engineering performance factor and saved 10% project cost.

Key words: project management, system dynamics, phase dependency, process, resource, scope, and target.

1. Introduction

Aibel As, a Norwegian based service company, which has core businesses in the oil, gas and renewable energy sectors, needed improved work performance with a reduced cost of construction. The company provides engineering, construction, upgrading, and maintenance services for both onshore and offshore systems. Despite the company has a presence in around half of the oil and gas offshore installation in the Norwegian continental shelf and in more than four onshore facilities in Norway, the current insurgence of South East Asian companies in the business area, together with a huge reduction of investment from the major players of the industry, has posed a halt to its fast growth (Interviewee 1; Interviewee 2; Abel News, March, 2013). Internal reports show that the company has faced strong competition in the business areas in which it has been well represented and even led them to lose some of the strong bids the company recently made. This has forced the company to consider several potential paths, such as a search for some promising business areas and intensify its investigation of its own project execution strategies.

A recent internal study shows that the engineering man-hours used in recently completed projects and on projects that are near to their completions, have significantly increased compared to similar previous projects. A study on four similar projects shows that, during the past 10 years, the man-hours used for engineering processes have increased up to 182%. The study also indicated that the discrepancy between initially estimated engineering man-hours and actually spent man-hours have increased from nearly 36% to 134% in the past 10 years. This is of concern because the engineering processes are the cornerstones that all the company's activities are founded on.

On the other hand, the search for promising business areas led to the identification of the renewable business area as one core business sector. Currently, the company is engaged in its first offshore wind energy (OWE) project under an Engineering, Procurement, Construction and Installation (EPCI) turnkey contract together with two other companies.

Since the commencement of the first OWE project in 1991, 2.5 km off the Danish cost at Viendby, commercial scale offshore wind facilities have been operating around the world, mainly in Europe (GWEC, 2012). Even though the first decade of the offshore wind power sector growth was mainly restricted to small near-shore projects,the increasing demand for energy and raising concern over greenhouse gases, together with advancements in OWE technologies and shortage of nearby coastal lines, have been pushing its development to ever deeper, increasingly further shores and to technologically complex locations (Arapogianni, et.al., 2011).

The construction of OWE turbines at sites far from shores, however, requires High Voltage Direct Current (HVDC) converter stations. This is because High Voltage Alternating Current (HVAC) transmission systems that connects the OWE turbines with onshore grids are not economically effective for distances above 60 to 70 km, mainly due to the associated high energy losses during transmission (Bresesti et.al., 2007; Stamatiou et.al., 2011). In line with this, a number of HVDC convertor substations are under construction and competition across companies in the supply chain for offshore wind is increasing with an influx of new entrants (Arapogianni, et.al., 2011).

In its first OWE project, Aibel builds DolWin Beta together with ABB and Drydocs World Dubai for a large wind farm cluster in the German sector of the North Sea. DolWin Beta will receive alternating current from three wind farms (a total of 240 wind turbines), and convert it into direct current before sending it onshore through subsea cables. It will have a capacity of 924 MW. DolWin Beta is the size of a football field. It is 70 meters tall, 74 meters wide and 99 meters long. Structurally, DolWin Beta has two main parts, HVDC convertor and a supporting structure. The supporting structure, in addition to the compartments for the HVDC converter, has separate living quarters for 24 people, a helipad and two lifting cranes.

Despite the promising business opportunity, "the high costs associated with the construction of converter substations have been creating problems in the company's competitiveness" in this rapidly growing market(Interviewee 1).

There are several alternative explanations for the high cost of offshore wind platform construction, including the immaturity of the technology in the subfield, an increase in the prices of construction materials, specifically, copper and steel, a shortage of construction yards, a need for high standardization since the platforms are towed in very hostile environments, and problems associated with supply chain and project management (Garrad Hassan, 2010; Arapogianni, et.al.,2011).

According to Interviewee 1, although there are "promising signs in the technological cost reductions of wind turbines", which could possibly pave directions for cost reductions in other substructures, the “technological efforts made towards achieving a 30% to 40% cost reduction for converter stations weren’t yet successful. Rather, the cost has increased by an additional 30%”.

Furthermore, most of the technologies under use in the construction of HVDC offshore wind energy converter stations are those adapted from the offshore oil and gas (EWEA, 2011). However, unlike offshore oil and gas, which could be “customized based on clients' specifications and site requirements, OWE converter stations need to be standardized” (Interviewee 1). Thus, Aibel AS managers are currently focusing on standardizing their project management methods, mainly by relying on already proven technologies and managing the construction value chains. So that the company could offset the high cost associated with the constructions, through lessons learnt, improved reliability, and structural efficiency.

Literature show that managing projects of such a kind is usually difficult because large-scale projects are extremely complex and highly dynamic (Abdel-Hamid &Madnick, 1991; Streman, 1992; Cooper & Lee, 2009; Arapogianni, et.al., 2011). Moreover, such projects involve both multiple feedback processes and nonlinear relationships (Abdel-Hamid &Madnick, 1991; Streman, 1992; Cooper & Lee, 2009). Thus, decisions made, solely based on human mental models, in managing such projects “cannot hope to account accurately for the myriad interactions, which jointly determine the outcomes of the projects” (Sterman, 1992). But the use of system dynamics tools can help managers identify the problems occurred in the workflows and their associated costs across the entire life of the projects (Abdel-Hamid &Madnick, 1991; Cooper & Lee, 2009). This is because“system dynamics is the application of feedback control systems, principles, and techniques to managerial, organizational, and socioeconomic problems”(Roberts, 1981, cited in Abdel-Hamid, 1984).

Given the company’s desire to investigate the high construction cost of HVDC offshore wind energy converter stations from a project management perspective and the problems that the company has discovered in its recent internal study, associated with one of its core business, engineering, this research has focused on investigating the impact of the engineering process on the construction cost of HVDC offshore wind energy converter stations with the help of a system dynamics model.

The first and primary purpose of the model is to enhance our understanding of the engineering process. Dubin (1971), cited in Abdel-Hamid (1984), claim that the "locus of understanding in a scientific model is to be found in its laws of interaction". Hence, with the help of the model, we wanted to gain a detailed understanding of how the various variables that constitute the engineering process interact with each other and explore what govern their interactions.

The second purpose of the model is to foster learning. Lyneis and Ford (2007) claim that one of the important applications of system dynamics models is fostering learning. Because the models help managers assess what went right and what went wrong in a project, model analysis may provide valuable insight of relevance in future projects. Hence, through examining how the engineering process of the DolWin Beta project evolves, we want to facilitate organizational learning.

This paper is organized as follows. A detail description of the model follows the introduction. In the third section, the results are presented. Discussion on model validation and behavior analysis are part of this section. In the fourth section of the paper, we analyze scenarios and discuss on policy recommendations. Finally, the paper closes with concluding remarks and recommendations for future study.

2. Model description

This study aims to increase understanding of the engineering process in the construction of HVDC offshore wind energy converter station and its dynamic impacts on construction costs. A system dynamics model is used to gain insight into the dynamics of the system and about the drivers underlying the high construction cost. The model is built on the basis of previously developed and tested project structures, mainly project structures developed by Abdel-Hamid (1984), Homer et.al. (1993), Ford (1995), and Cooper & Lee (2009).The section below describes the main structures of the model and the underlying ideas behind their formulation.

Model structure

Our underlying assumption in the formulation of the model structures is the cost performance of HVDC offshore wind energy converter substation construction could be affected by two major factors: a) factors that govern the flow of information about the progress of engineering works across different phases of the engineering process & b) factors that govern the flow of the engineering works within a single engineering phase.

a) Factors affecting the flow of workprogress information across engineering phases

From designing the architecture of the HVDC offshore converter substation on paper to 3D modeling of the substation structure, the engineering process passes through various phases. And each phase of the engineering process is constrained by the progress of the other phases to which it is dependant. In Aibel As, the engineering process is divided within three engineering units: System Engineering, Engineering for Procurement, and Area Engineering. Although the structural setup is the same across the three engineering units, each of the three engineering unit process different engineering activities in a semi-parallel setup.

The first activity in the engineering process is understanding what the project shall produce. In order to foster such understanding, system descriptions are created on the basis of a study of functional requirements. Such descriptions are illustrated with schematic drawings (usually on paper) and descriptive texts. System Engineering is responsible for such activities.

Once the system descriptions are ready, equipment that will constitute the final product will be ordered. The materials in the list are also predefined for 3D modeling. The engineering unit responsible for such activities is Engineering for Procurement. On the basis of the system description and the information about the equipment and part, a 3D model of the design is produced. Descriptions about how parts shall be assembled are also produced together with the 3D model. The Area Engineering unit does these activities.

The information flow about the progress of the engineering work across the engineering units is not unidirectional. For example, if the material specifications produced by the System Engineering unit are not to the standard and/ or the lists are not available in the market when checked by the Procurement for Engineering unit, the description list and/or the schematic drawings need to be revised by the System Engineering unit. Similarly, unless the standard of specified materials is assured and/ or their availability in the market is confirmed by the Procurement for Engineering unit, both the schematic drawings and the 3D designs cannot be approved for construction by the Area Engineering unit. Hence, the work progresses of the System Engineering unit constraints the progress of the other engineering units and vice versa.

In our model, we represented the three engineering units as three different phases of the engineering process. Each phase is customized to represent a specific stage of an engineering process. A phase dependence network describes the flow of information across the engineering units. Figure 1 represents the interaction across the three engineering phases.

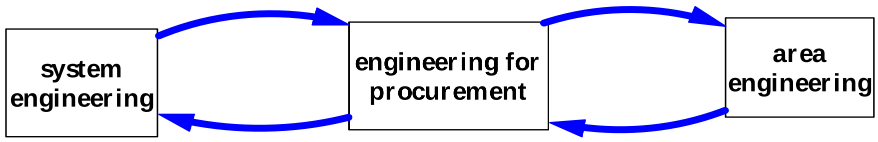


Figure 1 Interaction across engineering phases

The underlying assumptions regarding the interaction of the three engineering phases are as follows:

- The work progress in one engineering phase constrains the progress of a dependent engineering phase. The dependency network is shown by the arrows in Figure 1.
- The amount of engineering work in a phase is measured in a unit called Tasks. A Task can be anything, drawings, analytical solutions, material specification documents, 3D model codes... However, for operational reasons Task is defined as the amount of a project work that requires one normal work day of an experienced labor force, who has a "nominal potential productivity" level of one. A normal work day in the company is equivalent to 7.5 hours. Tasks flow within a single phase. However, Tasks do not flow across phases, - rather the information about the fractional progress flow across phases.
- The fractional values of the scope of work completed operates across related engineering phases, i.e. a 100% scope of work of an upstream engineering phase is equivalent to a 100% scope of work of a dependent, downstream engineering phase. However, the actual number of Tasks in these dependent phases could be different.
- Errors inherited by downstream engineering phases from upstream phases corrupt downstream work.
- Inherited errors that are discovered by downstream phases are returned to the phase where they are generated for a change.

b) Factors affecting the flow of engineering work within a phase

In addition to the work process constraints across engineering phases, the work progress in a single engineering phase could be constrained by a number of factors that determine its progress within its boundary. Literature claim that at least four major factors; actual work process in a particular phase, scope of the engineering work, resources allocated to the engineering work and targets set to be achieved in that particular phase constrain the progress of an engineering phase (Ford, 1995).

In our model, we represented the four factors as subsystems to the three engineering phases. Thus, each engineering phase has four subsystems: work process subsystem, scope subsystem, human resource subsystem and target subsystem. The subsystems are further subdivided into sectors. The interaction among the sectors and across the subsystems defines a phase. Figure 2 represents the interactions among the subsystems of a single engineering phase.

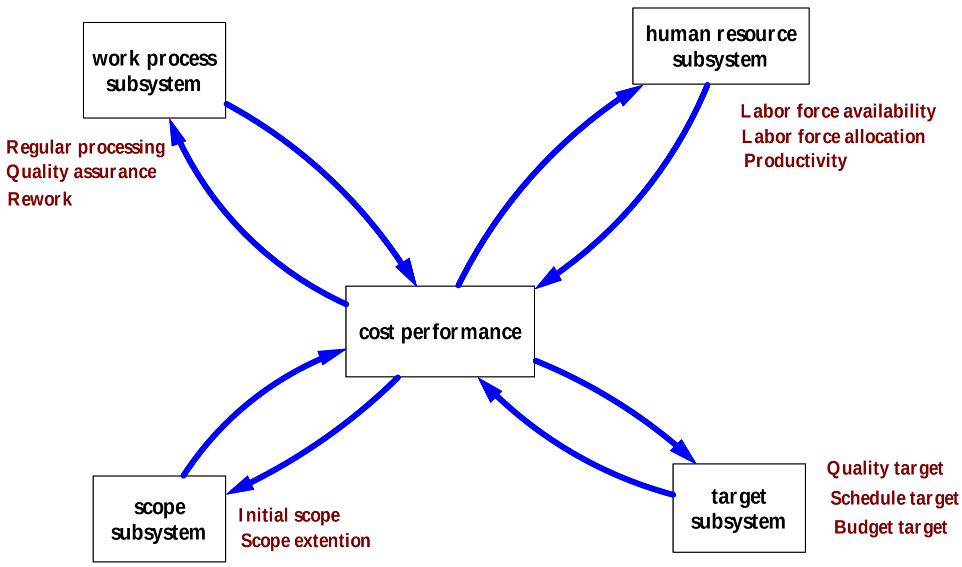


Figure 2 Interaction between subsystems in a single phase

The complete structure of the model is relatively large and not well suited for portrayal in a single picture. However, we summarized the central dynamics included in the system dynamics model for a single engineering phase in a simplified causal map as shown in Figure 3. The underlying assumptions in the interactions of the subsystems are described in the section below. However, a more detailed description of the model, the underlying assumption and more in depth analysis on the formulation of the mathematical equations can be found in the report of the first author's master thesis: https://bora.uib.no/handle/1956/8780

Assumptions in the interaction of subsystems in a single engineering phase:

- The rate of flow of tasks across the work process subsystem, which comprises regular processing, quality assurance, and rework, constrains the progress of the engineering works in a single phase.
- Availability of tasks and labor force together with the productivity level of the labor force and the quality of practice determines the rate of flow of tasks.

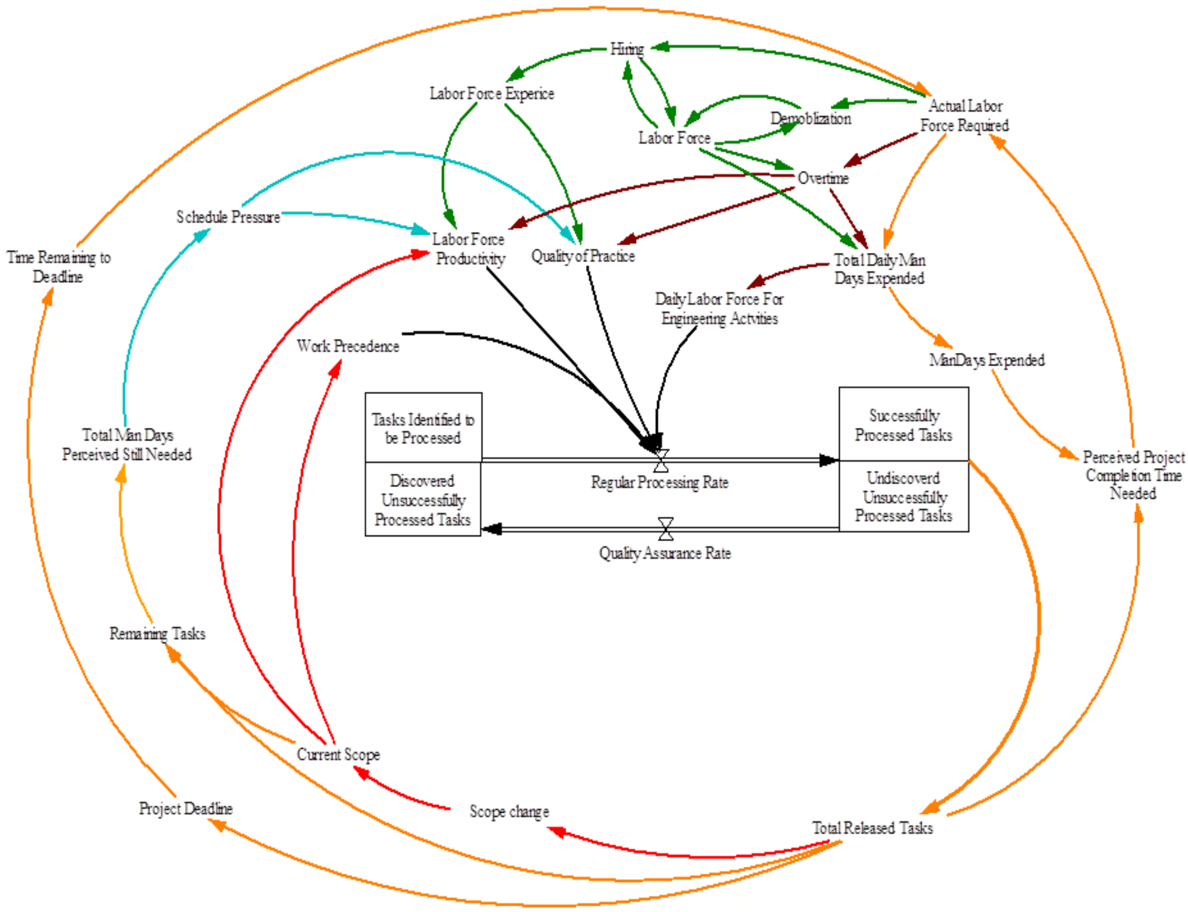


Figure 3. Centeral dynamics represented in the system dynamics model

- Internal and External task precedence relations together with the phase's scope constrain the availability of tasks, whereas the hiring and firing decisions determine the labor force size.
- Poor performance on project targets affects the productivity of the labor force and the quality of practice of the engineering process, which, in turn, constrains the rate of flow of tasks and the phase's progress.

In order to provide a better picture on the formulation of the model, we also presented the central stock and flow structure of the work process subsystem of a single engineering phase in Figure 4. This structure has served as a backbone in the formulation of the system dynamics model. The core structural components of the work process subsystem are adopted from the new product development model of Ford (1995), with some modifications. The discussion below explains the principal interactions among the stocks and flows.

In a single phase, all the engineering works, which are measured in Tasks, must pass a minimum of four stocks before they have been completely processed and released to the downstream phase.

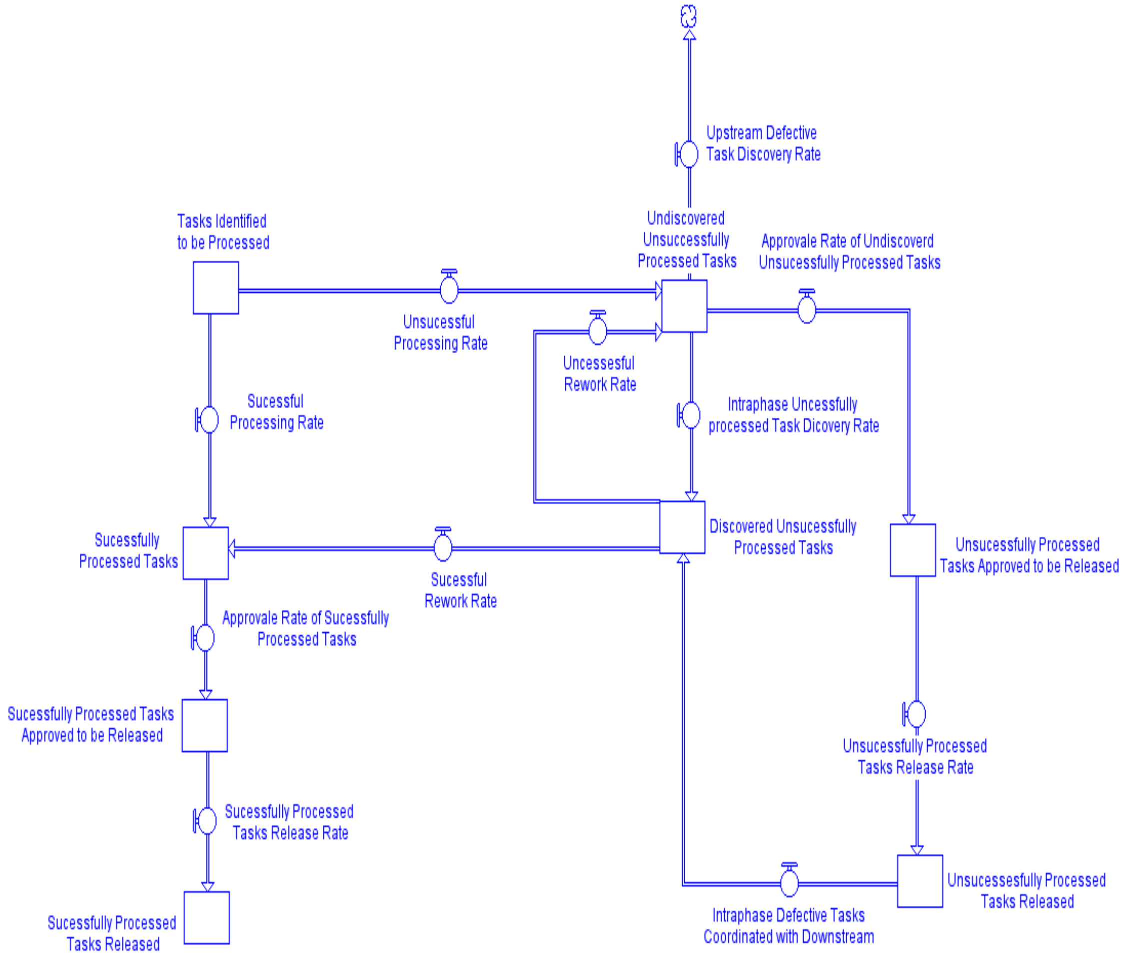


Figure 4 Stock and flow structures of the work process subsystem in a single phase

Initially, all the tasks of a phase, those that are identified during the contract award and those discovered in later stages of the phase, accumulate in the “Task Identified to be Processed” stock. Depending on the performance of the task processing rate and the quality of practice in processing, the tasks, then move onto either the “Undiscovered Unsuccessfully Processed Tasks” stock or to the “Successfully Processed Tasks” stock. All the processed tasks, then pass through a quality assurance activity. The quality assurance activity has two objectives, the first one is to approve successfully processed task and the second one is to uncover unsuccessfully processed task.

If the quality assurance activity discovers unsuccessfully processed tasks and if the errors are generated within the phase, the flawed tasks move to the “Discovered Unsuccessfully Processed Tasks” stock for rework. Successfully reworked task, then move to “Successfully Processed Tasks” stock and the unsuccessful ones back to the “Undiscovered Unsuccessfully Processed Tasks” stock for further inspection. If the errors are made outside the phase, then the flawed tasks move to the “Discovered Unsuccessfully Processed Tasks” stock of the upstream phase so that they can be reworked in the phase in which they were generated.

On the other hand, undiscovered unsuccessfully processed tasks accumulates temporarily in the “Unsuccessfully Processed Tasks Approved to be Released” stock to be delivered to the downstream phase. Similarly, successfully processed tasks that pass through the quality assurance activity, accumulate in the “Successfully Processed Tasks Approved to be Released” stock for release. The temporarily accumulated tasks are then released to downstream phases.

One of the structural differences between Ford’s (1995) and our model is that our model, for operational reasons, does not mix successfully and unsuccessfully processed tasks in the later stages of the work process. Operationally, stocks allow complete mixing of their contents (Sterman, 2000). Thus, if we did not disaggregate successfully and unsuccessfully processed tasks, there could be residuals inside the stocks that accumulate the two types of processed tasks. However, disaggregation of the two types of processed tasks gives us an opportunity to investigate the sole effect of flawed tasks on the progress of the engineering phase, in particular and on the entire project progress as a whole. It also allows us to investigate the sole impact of flawed tasks on the nonconformance of the engineering phase to its targets.

A second structural difference between our model and Ford’s is that in our model we have not explicitly described a possible coordination that could exist across phases, particularly when a downstream phase identifies errors done by an upstream phase. This is for a good reason of simplicity. From our discussions with the company’s managers, particularly with Interviewee 2, and from our document analysis, we have learned that employees are “not interested in registering neither the errors they made nor the errors done by their work colleagues”. Although, they are supposed to register the errors discovered in a “Non-Confirmatory

Report”, this practice seem to be neglected. According to Interviewee 2, the employees “did not want to look as stupid” by either registering their own errors or those of their work colleagues’. They, rather, immediately update each other so that the people who generate the errors can act on them. Furthermore, there are “no incentives for registering errors” as the customers are not “responsible for compensation of quality costs”. Thus, in our model, discovered flawed tasks are sent immediately to the appropriate destinations for rework.

3. Model Validation and behavioral analysis

Model validation is one of the important steps in the system dynamics methodology. The purpose of model validation is to build confidence in the usefulness of the model for the intended purpose (Barlas, 1996). Confidence in models can be built by a variety of tests, including model’s structural tests, behavioral tests and policy implications (Forrester and Senge, 1979).

In order to build confidence in our model, we carried out structural and behavioral tests. The model structure tests conducted includes structure and parameter verification tests, dimensional tests (unit consistency test), and extreme condition tests. The model has passed all the tests.

Structure and parameter verification tests were carried out on the basis of a series of interviews with the company’s managers, surveys, document analyses, and previous research findings. The model structure is also exposed to the managers of the company for criticism, then revised, and again and again exposed in an iterative process.

Of the different behavior analysis tests (see Forrester & Senge, 1979 for details), we carried out behavior reproduction (comparison between simulated and actual behavior) and sensitivity analysis.

a) Comparison of Model Simulations to DolWin Beta Project

The main objective of this test is to examine the model’s ability to reproduce the historical dynamic behavioral patterns observed in the engineering process of the DolWin Beta project. In order to simulate the model, four sets of parameters for the subsystems of the engineering phases (work process, human resource, scope and target) were needed to be set. The parameters were estimated on the basis of interviews and document analysis (see Appendix Tables 1- 5 and Figures 1-5).

Once the model had been parameterized, it was run to simulate the DolWin Beta project. The model was run for 712 project work days, which is the project life time agreed between the customer and the company. It is a fixed deadline. The company also sets an internal deadline for the engineering process so that 70% of the engineering work could be completed before construction activities are started. The internal deadline is set to the 187th project day.

There are two basic reasons behind the company's motive in introducing internal deadline. The first is to minimize the amount of engineering reworks that could possible be initiated when engineering design errors are discovered during construction activities. The second reason is to reduce the entire project deadline by starting construction activities as early as possible, with the most readily available and matured engineering designs.

Figures 5(a-d) portray the comparison between the simulated (blue) and actual work progress (red) of the three engineering activities and the entire engineering process. During most of the development period of the project, the model replicates the actual work progress in both the individual engineering phases and the overall engineering process.

Although the overall fit between the simulated and the actual engineering work progress in all the engineering phase is acceptable, there are some points that need explanation. For example, on the 167th project day additional engineering works are added to the scope of the phase, reducing the overall progress of the phases correspondingly in system engineering (by 6%) and in area engineering (by 1%).

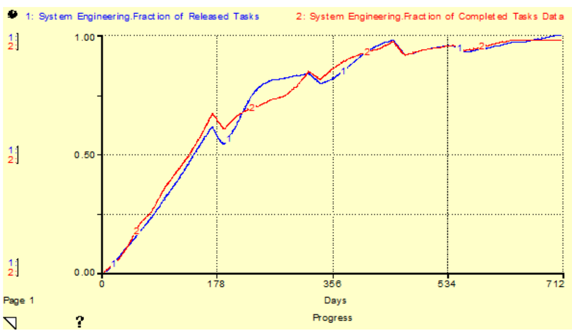


Figure 5a. Work progress in System Engineering phase

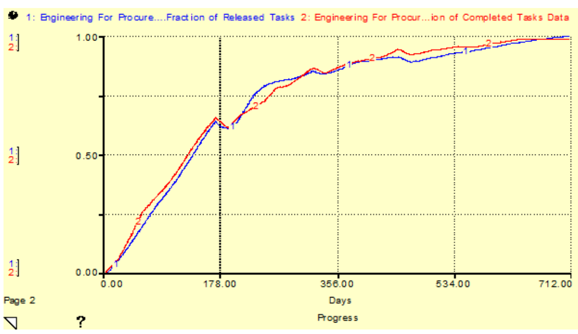


Figure 5b. Work progress in Engineering for Procurement phase

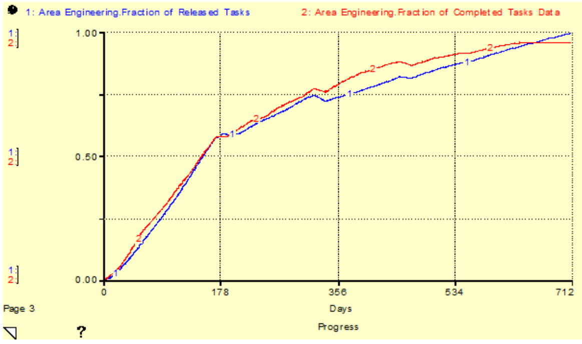
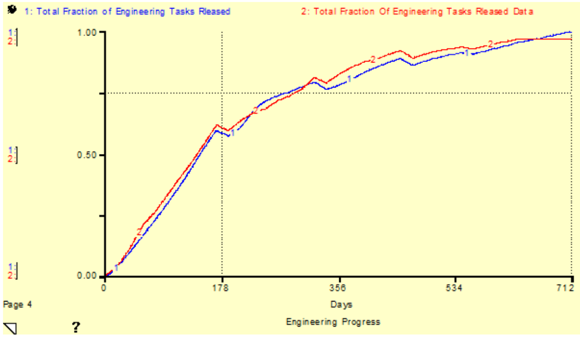
	

Figure 5c. Work progress in Area Engineering phase	Figure 5d. Work progress in Overall Engineering

The additional scope of work come to picture at the time when the phases approached their internal deadline, initially set to the 187th project day. The additional scope of the work, together with the motive for complying with the internal deadlines, forced engineering to recruit more labor force, as can be seen in Figures 6a-d.

One noticeable difference between the simulated and the actual labor force shown in the figures below is, in the historical labor force curve the additional labor force had started to join the engineering units one month earlier than the additional scope of work is introduced. This implies that the managers were primed to expect a change in scope much earlier. However, the model only recognizes the change in scope, when it actually is introduced, and hence, the simulated labor force lags behind the actual labor force.

Another point that needs explanation is the deviation of the simulated curve from the actual progress in Figures 6, starting from the 220th project day, specially in the system engineering phase and Engineering for Procurement phase. This is, of course, due to the presence of a relatively larger labor force in the phases after the internal deadline.

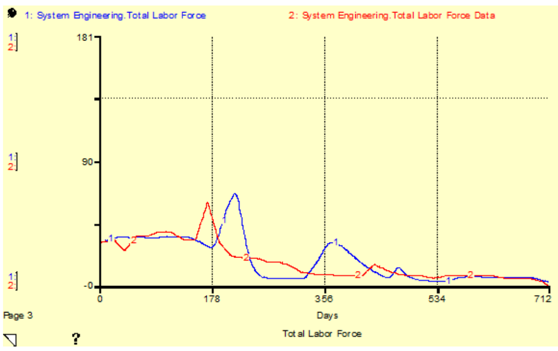
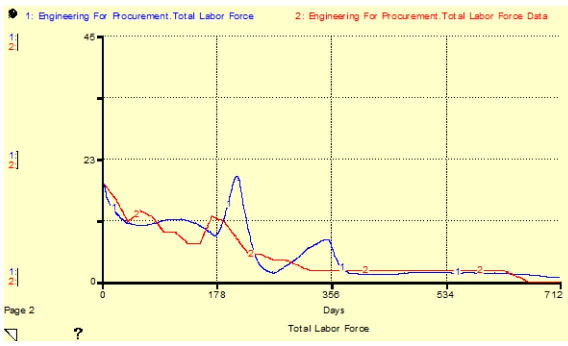
	

Figure 6a. Total labor force in System Engineering phase	Figure 6b. Total labor force in Engineering for Procurement phase

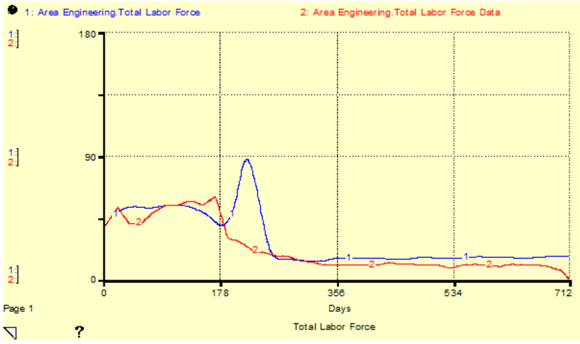


Figure 6c. Total labor force in Area Engineering phase

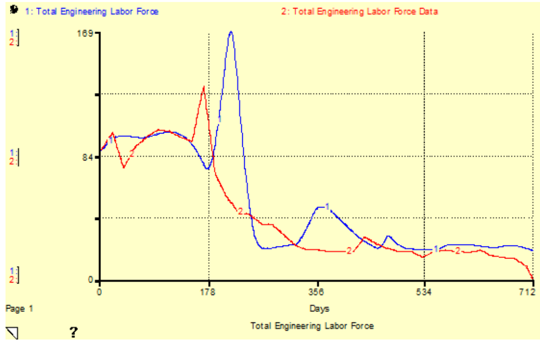


Figure 6d. Total Engineering labor force

In the formulation of the model, we assumed that it takes some time before the managers adjust the labor force affected by the initial internal deadline to the new deadline. We also assumed that the labor force cannot sit idle as long as there are available engineering tasks to handle. Hence, this has resulted a slight increase in the progress of the system engineering and engineering for procurement phases.

However, the presence of a large labor force in the area engineering did not bring the increase in progress as it did in the above two phases. This is due to the effects of the work precedence constrains from the upstream phases on the amount of tasks that are made available to the area engineering phase. As shown in the progress curves of Figure 5, only a small amount of work is added to the scope of the area engineering, while a relatively larger amount of work is added to the scopes of the upstream phases. This resulted in a relatively larger drop in progress in the upstream phases of the area engineering. (More engineering tasks become available in the area engineering phase only when its upstream phase shows a relatively larger progress). Hence, the area engineering phase showed little progress during those periods.

The third model output compared with the DolWin Beta historical behavior is the cumulative man-hours expended. The results of the model run are portrayed in Figures 7a-d. The comparison between the simulated (blue) and actual (red) cumulative expended man-hours in the three engineering activities and in the entire engineering process shows that the model replicated the actual expended man-hours in most of the development period. However, the deviations observed in late stages of the System Engineering and Engineering for Procurement phases could be explained by the views of the two managers we interviewed (Interviewee 1; Interviewee 2).

We learned that the labor force, who actually did the engineering job, is the one who records the expended man-hours and, often, the man-hours could be recorded much later in the project period. For example, a labor force could record all his/her man-hours at the end of the month. However, man-hour reports are generated every week and the man-hours done by this particular labor force, would be missed from the three prior weeks reports and would be presented in the last report as if they are done in that reporting week.

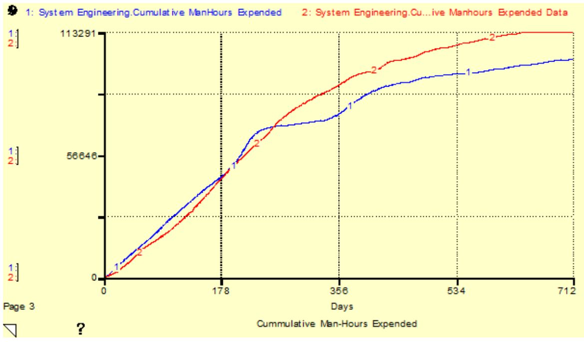


Figure 7a. Cumulative Expanded Man-Hour in System Engineering phase

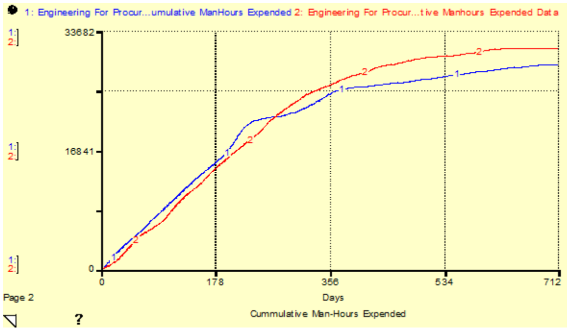


Figure 7b Cumulative Expanded Man-Hour in Engineering for Procurement phase

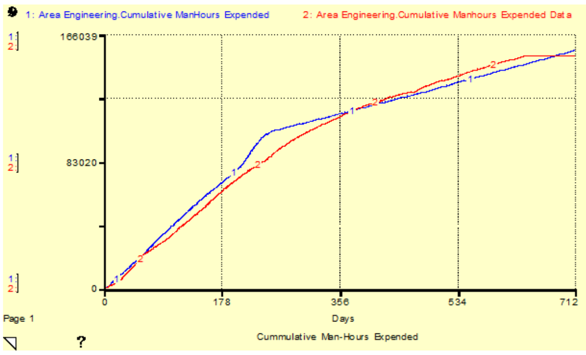


Figure 7c. Cumulative Expanded Man-Hour in Area Engineering phase

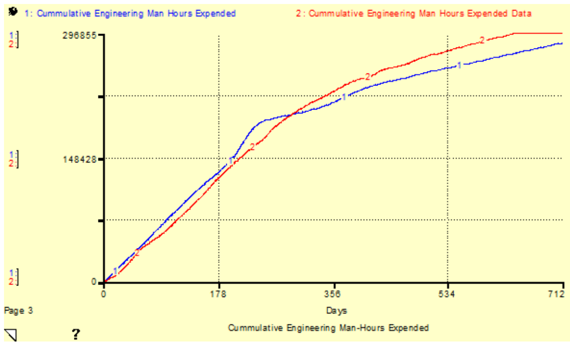


Figure 7d. Cumulative Expanded Man-Hour in the entire Engineering

Besides this, the man-hours could be recorded against a wrong engineering phase or to a wrong project phase. For example man-hours used in System Engineering could be recorded in Area Engineering or Engineering for Procurement, and sometimes even outside of the engineering phases, say in the construction or testing phases of the project. There are departments that redistribute wrongly recoded man-hours to the appropriate engineering phases, but such activity usually takes a very long time. Hence, the observed deviations could be accounted for either of these two reasons. Despite this devotion, we believe that the model has replicated the cumulative expended man-hours with an acceptable fit.

b) Sensitivity Analysis

Sensitivity analysis is made to ascertain whether or not plausible shifts in the model parameters can cause a model to fail behavior test previously passed. Specially, sensitivity analysis is conducted, on parameter values that are estimated based on statistical data and expert knowledge, or parameter values obtained from other research works (Forrester & Senge, 1979).

We carried out sensitivity analysis on selected parameters from three subsystems: work process, human resource and target subsystems. The selected parameters and their values are listed in Table 1. The values in Table 1 are taken from the System Engineering phase; however, the same procedure was applied in the other two engineering phases too.

Table 1. Parameters for Sensitivity analysis

Subsystem	Parameter	Sensitivity test scenario		
		Optimistic (-50%)	Baseline scenario	Pessimistic (+50%)
Work Process	Minimum Regular Processing Duration per Task	0.5 days	1 days	1.5 days
	Minimum QA Duration per Task	0.065 days	0.13 days	0.195 days
	Minimum Rework Duration per Task Discovered in the Phase	0.065 days	0.13 days	0.195 days
	Minimum Rework Duration per Task Discovered outside the phase	0.25 days	0.5 days	0.75 days
	Time to Release Tasks	2.5 days	5 days	7.5 days
	Internal Precedence	Open	Hyperbola	Linear
	External precedence - System Eng. on Eng. for Procurement	Open	Linear	"S" shaped
	External precedence - Eng. For Procurement on Area Eng.	Open	Hyperbola	Linear
Human Resource	Initial total work force	16	31	46
	Avg Assimilation Time of New Employees	30 days	60 days	90 days
	Avg Assimilation Time of Transferred-In Company Employees	10 days	20 days	30 days
	Avg Assimilation Time of New Hire-In Externally	10 days	20 days	30 days
	Demobilization delay	5 days	10 days	15 days
Target	Maximum Internal Deadline Extension Dates	20 days	40	60
	Max Time to Adjust Labor Force Affected by Internal Deadline	10	20	30
	Initial quality goal	0.8	0.9	1

We took the parametric values that replicated the historical value as a reference and carried out sensitivity analysis by adding and subtracting 50% of the reference parameter values. We considered the parametric values above the reference values as "Pessimistic" values and those below the reference as "Optimistic" values. The reference values are referred as "Baseline" values. Exceptions to our plus or minus 50% consideration are the work precedence parameters. In the work precedence parameters, we considered hyperbolic, “S” shaped, linear and open (unconstrained) relations.

Sensitivity is measured in the range of changes in the project performance due to changes in parameter values. We measured project performance in cycle time, quality and cost. Cycle time is the time required for effectively all processed tasks to be released. Since the DolWin Beta project has a fixed deadline (712 project days), we measured the engineering process performance in terms of completing all the engineering works on or before the project deadline. Quality is measured in terms of the total number of unsuccessfully processed tasks released. Cost is the cumulative of all the payments made in an engineering phase to the labor for the service they provided in the engineering phase.

Tables 2a-c presents the percentage of range of performance change in cost and quality across the three engineering phases, whereas Figures 8a-f depicts a range of performance change in cycle time. The baseline performances, deviations from baseline, and percentage of change from baseline can be accessed from the master thesis: https://bora.uib.no/handle/1956/8780

Table 2a. Range of performance change in percent in System Engineering Phase

Subsystem	Parameter	% Cost Performance Range	% Quality Performance Range
Work Process	Minimum Regular Processing Duration per Task	15	28.31
	Minimum QA Duration per Task	11.98	9.04
	Minimum Rework Duration per Task Discovered both inside and outside the phase	0.02	0
	Time to Release Tasks	0.35	13.25
	Internal Precedence	659.13	54.82
	External precedence	9.84	22.89
Human Resource	Initial total work force	1.77	30.12
	Avg Assimilation Time for all new project members	1.13	69.88
	Demobilization delay	0.72	10.84
Target	Maximum Internal Deadline Extension Dates	1.11	53.01
	Max Time to Adjust Labor Force Affected by Internal Deadline	0.04	0.00
	Initial quality goal	0.00	0.00

Based on the results in the range of performance changes, we can conclude that the two performance measures (cost and quality) are more sensitive to the internal and external precedence parameters. In addition to this, performance in quality is more sensitive to initial workforce size and avergage assimilation time for new project members across the three engineering phases. However, the model is insensitive to initial quality goal and minimum rework duration.

Table 2b. Range of performance change in percent in Engineering for Procurement Phase

Subsystem	Parameter	% Cost Performance Range	% Quality Performance Range
Work Process	Minimum Regular Processing Duration per Task	27.87	0
	Minimum QA Duration per Task	14.54	16.67
	Minimum Rework Duration per Task Discovered both inside and outside the phase	0.00	0.00
	Time to Release Tasks	3.71	0.00
	Internal Precedence	503.78	41.66
	External precedence	463.89	0
Human Resource	Initial total labor force	1.82	33.33
	Avg Assimilation Time for all new project members	0.81	50
	Demobilization delay	1.99	8.33
Target	Maximum Internal Deadline Extension Dates	2.15	8.33
	Max Time to Adjust Labor Force Affected by Internal Deadline	0.00	0.00
	Initial quality goal	0.00	0.00

Table 2c. Range of performance change in percent in Area Engineering Phase

Subsystem	Parameter	% Cost Performance Range	% Quality Performance Range
Work Process	Minimum Regular Processing Duration per Task	14.47	9.09
	Minimum QA Duration per Task	43.45	3.9
	Minimum Rework Duration per Task Discovered both inside and outside the phase	0.01	0.00
	Time to Release Tasks	10.96	1.30
	Internal Precedence	298.84	16.88
	External precedence	310.14	32.46
Human Resource	Initial total labor force	5.56	76.63
	Avg Assimilation Time for all new project members	1.75	44.16
	Demobilization delay	1.32	6.49
Target	Maximum Internal Deadline Extension Dates	1.5	27.27
	Max Time to Adjust Labor Force Affected by Internal Deadline	3.64	0.00
	Initial quality goal	0.00	0.00

The figures shown below also confirm that the cycle time performance of the model is more sensitive to the internal and external precedence of the model. As shown in Figures 8a-f the project couldn't be completed within the deadline when the internal and external work precedencies are set to pessimistic (linear and "S"- shaped) relations.

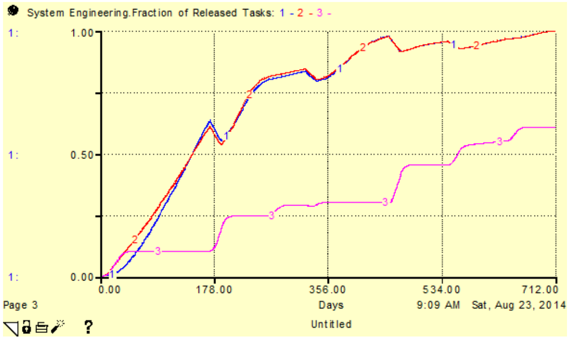


Figure 8a. Progress of System Engineering phase under Internal precedence parameter

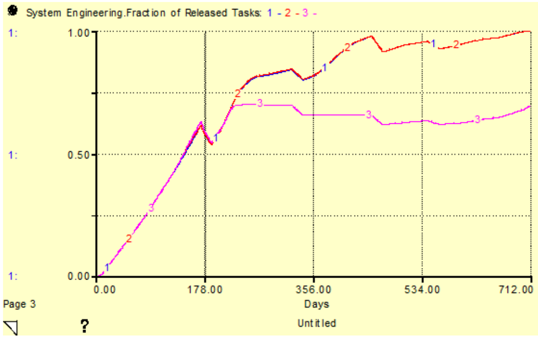
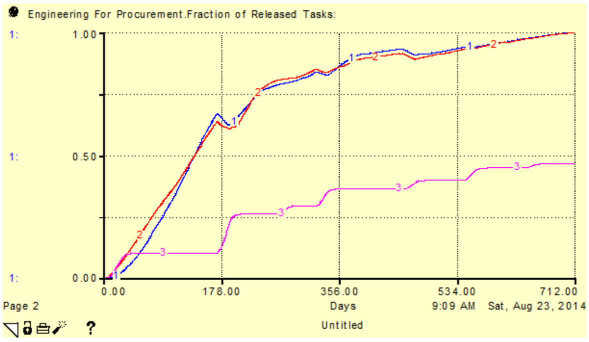


Figure 8b. Progress of System Engineering phase under External precedence parameter



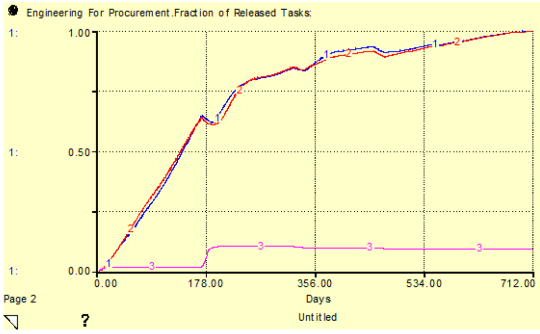
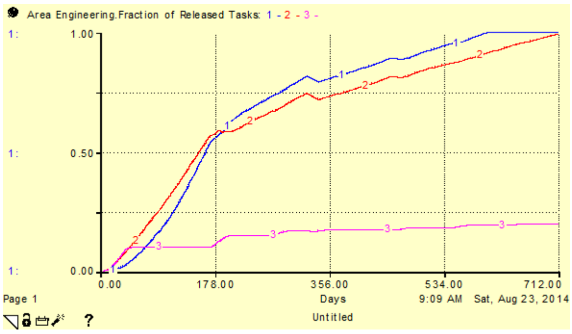


Figure 8c. Progress of Engineering for Procurement phase under Internal precedence parameter

8d. Progress of Engineering for Procurement phase under External precedence parameter



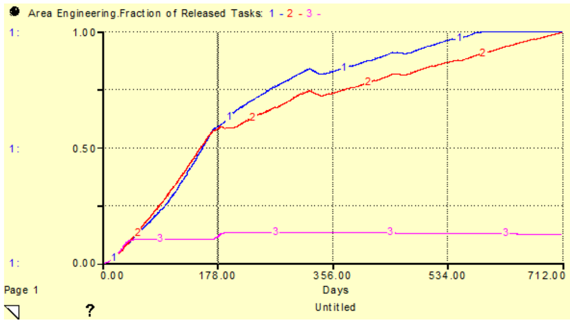


Figure 8e. Progress of Area Engineering phase under Internal precedence parameter

Figure 8f. Progress of Area Engineering phase under External precedence parameter

4. Policy Analysis

In this section, we mainly focus on examining scenarios on selected variables, which could serve as future policies. As we have explained in the earlier sections, the main objective of this research is to investigate the drivers for the high cost of construction with the help of system dynamics methodology. From the sensitivity analysis we made in section 3, we have realized that the model is very sensitive to the work precedence relation parameters. However, these parameters are exogenous to our model and very specific to the work process of the company.

Hence, we opted for carrying out our scenario analysis on the internal deadline and project deadlines of the company and evaluate their effect on cost, cycle time and quality. As we indicated in section 3, the company has two deadlines, internal and external. The internal deadline is set for the 187th project day with a possible extension of 40 project days, whereas the project deadline is set for the 712th project day, which is actually equal to the final project completion date of the DolWin Beta project and it is fixed. The main objective of the internal deadline is to complete 70% of the engineering work as early as possible, so that construction activities can be started early in the project.

We had chosen seven different scenarios and assessed how the change in internal and project deadlines affects the project's performance. The scenarios are shown in Table 3. The first scenario is the baseline, which we used to compare the project's performance in the other scenarios against the performance in it.

Table 3. Scenario description

S.No	Scenario	Description
1	Baseline	Fixed project deadline (712 days) with internal deadline (187 days)
2	Scenario 2	Only fixed project deadline (712 days)
3	Scenario 3	Flexible project deadline (712 + 400 days)
4	Scenario 4a	Fixed project deadline (712 days) with internal deadline (187 + 40 days)
5	Scenario 4b	Fixed project deadline (712 days) with internal deadline (187 - 40 days)
6	Scenario 4c	Fixed project deadline (712 days) with internal deadline (187 + 80 days)
7	Scenario 4d	Fixed project deadline (712 days) with internal deadline (187 - 80 days)

The performance of the three engineering phases in the three performance indicators is summarized in Table 4. From the table, we can see that (notice the colored cells; green is for the lowest and orange is for the highest) the baseline scenario has the lowest aggregate cost (192.15 MNOK), whereas Scenario 2 has the highest cost (455.3MNOK, a relative increase of 1.37 from the baseline). This second scenario has also the highest number of flawed tasks released (15.22 defects, a relative increase of 4.7 from the baseline scenario). On the other hand Scenario 3 has the lowest flawed tasks released. But this scenario has the highest cycle time (project completion time) and it takes a minimum of 597 project days (approximately 2.5 years) to start construction activities with this scenario.

The minimum project completion time with the earliest construction starting date (127 project days, a relative reduction of 0.4 from the baseline) can be achieved with Scenario 4c, which has an internal deadline of 80 project days less that the reference. However, scenario 4c compared to the reference has a relative increase of 0.3 in cost and a 1.4 relative increase in defective tasks.

Table 4. Performance indicators for different scenarios

S.No	Scenario		Cost Performance (in MNOK)				Unsuccessfully Processed Released Tasks (in # defects)				Cycle Time (in Workdays)	Early Construction Starting Day
			System Eng	Eng. for Proc	Area Eng	Total Eng	System Eng	Eng. for Proc	Area Eng	Total Eng	Total Eng	Total Eng
1	Baseline		65.90	18.51	107.74	192.15	1.40	0.13	1.14	2.67	742	212
2	Only fixed project deadline (712 Project day)		81.88	23.17	350.25	455.30	12.57	0.24	2.41	15.22	742	554
3	Flexible project deadline (712 + 400 days)		64.10	18.85	189.50	272.45	1.21	0.04	0.65	1.90	850	597
4	Fixed project deadline with new internal deadline of	4a) 187+ 40	72.27	19.74	174.69	266.72	2.72	0.28	4.15	7.15	739	261
		4b) 187 – 40	71.57	20.15	167.09	258.81	2.26	0.21	3.54	6.01	737	169
		4c) 187 – 80	69.97	21.71	160.04	251.72	2.13	0.28	4.04	6.45	736	127
		4d) 187 + 80	71.55	20.13	186.06	277.74	3.65	0.37	3.81	7.83	740	309

From the scenario analysis, we can conclude that internal deadlines are vital in order to successfully complete an engineering work within the scheduled deadline and with a relatively reduced project cost. However, the decision for a better scenario lies on the trade off between cost, quality of work and motive for early construction startup. Since the construction activity is outside our boundary, our recommendation for better scenario would be limited. However, we believe that this scenario analysis could give a good insight for managers to make their decisions. Given the scenarios shown above and their analysis, we recommended Scenario 4c (a fixed project deadline with an early internal deadline, approximately 1/5 of project deadline).

5. Conclusion and recommendation

The reduction of project cost has become a high priority for many construction companies who are looking for ways to become more competitive and to accomplish more with given resources. Yet large, complex development projects often experience substantial cost overruns. This research investigated the impacts of dynamic project structure, particularly the engineering process, on the construction cost of HVDC offshore wind energy converter substation.

A dynamic simulation model of multiple engineering phases was built using the system dynamics methodology. The model integrated several previously developed and tested project structures. Simulations describe the behavior generated by the interaction of customized engineering phases and a project management structure. Each phase explicitly models the impacts of work process, resource capacity, scope, and targets on three engineering activities: regular processing, quality assurance, and rework.

Project performance is measured in cost, cycle time, and quality. The model was calibrated to the DolWin Beta project of Aibel AS. Quantitative and qualitative data concerning the engineering process in general, and the DolWin Beta project in particular was collected for parameter estimation through interviews, surveys and document analysis. Sensitivity tests indicate that cost and quality are most sensitive to work precedence relations.

Comparison between simulated and historical records show that when the model is appropriately parameterized, the resulting simulated behavior closely resembles the actual historical behavior of the project. The similarity in behavior modes between the project behavior and model simulations supports the model's ability to simulate the dynamic engineering process.

The model was applied to the investigation of schedule completion date policies for improved project performance. Seven different schedule completion scenarios were tested. Model simulations indicate that internal deadlines are vital for the successful completion of engineering works and a project could be more benefited when internal deadlines are set around the 1/5 of the planned project deadline.

The company feels confident that the dynamic model does a good job of representing their typical engineering process and allows them to do strategic analysis with greater precision and understanding of the problem as a whole. A follow up discussion with the company’s managers reveal that the company is applying SD principles in one of its newly started projects and benefiting from it. From the application of concepts associated early personnel planning and recruitment to the project, sharing of common project goals and targets among project personnels, and also from reduction of unnecessary communication channels between employees and employees & project managers, the company achieved a 0.9 engineering performance factor; which is measured by dividing the number of engineering man-hours expended by the planned engineering man-hours. The company also saved 10% of the project cost for the customer from its start up engineering works.

In this research work, there were three delimitations, which we have not accounted well enough: scope of the model, model aggregation level and sources of data. The model was delimited only to the engineering process, but we believe that a complete picture about the cost drivers of big construction projects such as DolWin Beta, can be achieved through a full understanding and representation of the entire project phase. We also believe that a further disaggregation of the three engineering units could offer a much better understanding of the engineering process than what our model has offered. Finally, we want to point out that only few managers, who are involved in DolWin Beta project, estimated most of the parameters used in the model. However, a better estimation of parameters could be achieved if more managers from other projects of the company were involved.

Thus, on the bases of our delimitations we recommended a further study on the entire project execution strategy of the company, including construction, procurement, installation, and testing. We also suggest addition of model structures, which endogenize our exogenous inputs such as resource availability, scope extensions and development activity priorities.

Acknowledgement

I would like to express my sincere appreciation and gratitude to my supervisor, Professor Pål I. Davidsen, from the university of Bergen, Norway, for his valuable advice, comments and unreserved guidance throughout the master thesis. I am very grateful to extend my thanks to Geir-Ivar Vinsjevik and Tore Engevik, from Aibel As, for offering me the chance to carry out this research work on Dolwin Beta Project, for their continuous engagement during the modeling activity and for their assistance in the data collection.

References

Abdel-Hamid, T. K. (1984). The dynamics of software development project management: An integrative system dynamics perspective (Doctoral dissertation, Massachusetts Institute of Technology).

Abdel-Hamid, T. K., & Madnick, S. E. (1991). Software project dynamics: an integrated approach. Englewood Cliffs: Prentice Hall.

AibelNews (2013, March). International magazine for Aibel AS. No.1

Arapogianni, A., Moccia, J., Williams, D., & Phillips, J. (2011). Wind in our Sails–The coming of Europe’s offshore wind energy industry. The European Wind Energy Association (EWEA).

Barlas Y. (1996). Formal aspects of model validity and validation in system dynamics.

System Dynamics Review 12: 183-210.
Bresesti, P., Kling, W. L., Hendriks, R. L., & Vailati, R. (2007). HVDC connection of offshore wind farms to the transmission system. Energy Conversion, IEEE Transactions on, 22(1), 37-43.
Cooper, K., & Lee, G. (2009, April). Managing the Dynamics of Projects and Changes at Fluor. In Proceedings of the International System Dynamics Conference. Albuquerque 2009.
EWEA European Wind Energy Association Annual Report (2011)
Ford, D. N. (1995). The dynamics of project management: an investigation of the impacts of project process and coordination on performance (Doctoral dissertation, Massachusetts Institute of Technology).
Ford, D. N., & Sterman, J. D. (1998). Dynamic modeling of product development processes. System Dynamics Review, 14(1), 31-68.
Forrester, J. W., & Senge, P. M. (1978). Tests for building confidence in system dynamics models. Cambridge: System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology
Garrad Hasssan(2010). Offshore wind energy supply chain opportunity. Garrad Hassan and Partners Limitted
GWEC (2012). Global wind report annual market update 2012, report of Global Wind Energy Council
Homer, J., Sterman, J., Greenwood, B., & Perkola, M. (1993). Delivery Time Reduction in Pulp and Paper Mill Construction Projects: A Dynamic Analysis of Alternatives. System Dynamics Conference.
Lyneis, J. M., & Ford, D. N. (2007). System dynamics applied to project management: a survey, assessment, and directions for future research. System Dynamics Review, 23(2-3), 157-189.
Stamatiou, G., Srivastava, K., Reza, M., & Zanchetta, P. Economics of DC wind collection grid as affected by cost of key components. Volume 15 Wind Energy Applications, 4177.
Sterman, J. D. (1992). System dynamics modeling for project management. Unpublished manuscript, Cambridge, MA.
Sterman, J. (2000). Business Dynamics: Systems Thinking and Modeling for a Complex World. Irwin McGraw-Hill: New York.

Appendix

Table 1 Parameter estimates for the Work Process Subsystem

Parameter	Engineering Phase		
	System Engineering	Procurement for Engineering	Area Engineering
Minimum Regular Processing Duration per Task	1 days	1 days	1 days
Minimum QA Duration per Task	0.13 days	0.13 days	0.13 days
Minimum Rework Duration per Task Discovered in the Phase	0.13 days	0.13 days	0.13 days
Minimum Rework Duration per Task Discovered outside the phase	0.5 days	0.5 days	0.5 days
Time to Release Tasks	5 days	5 days	5 days

Table 2a Parameter estimates for the Human Resource Subsystem – Quality of Practice Sector

Parameter	Engineering Phase		
	System Engineering	Engineering for Procurement	Area Engineering
Reference Quality of Practice in Regular Processing	0.8 Unitless	1 Unitless	0.9 Unitless
Reference Quality of Practice in Rework	0.9 Unitless	0.9 Unitless	0.9 Unitless
Reference Quality of Practice in QA	0.9 Unitless	0.9 Unitless	0.9 Unitless
Probability to be Defective from Inherent Task Complexity	0.2 Unitless	0.05 Unitless	0.1 Unitless

Table 2b Parameter estimates for the Human Resource Subsystem – Labor Force Sector

Parameter	Engineering Phase		
	System Engineering	Engineering for Procurement	Area Engineering
Initial number of Experienced Employees	25 People	14 people	31 people
Initial number of Transferred-In Company Employees	0 People	0 People	0 People
Initial number of New Employees	0 People	0 People	0 People
Initial number of Experienced Hired-In Externally	6 people	4 people	8 people
Initial number of New Hired-In Externally	0 People	0 People	0 People
Avg Assimilation Time of New Employees	60 days	60 days	60 days
Avg Assimilation Time of Transferred-In Company Employees	20 days	20 days	20 days
Avg Assimilation Time of New Hire-In Externally	20 days	20 days	20 days
Avg Hiring Time of New Employees	40 days	40 days	40 days
Mobilization Delay	10 days	10 days	10 days
Avg Hiring Time of New Hire-In Externally	14 days	14 days	14 days
Demobilization Delay	10 days	10 days	10 days
Avg Employment Duration of Hire-In Externally	220 days	220 days	220 days
Experienced Employee Quit Fraction	0.05/year ≈ 0.0002/days	0.0002/days	0.0002/days
Max Hire-In Fraction Allowed	0.3 Unitless	0.3 Unitless	0.3 Unitless
Max New Hires Per Full Time Experienced Labor Force	2 People/People	1 People/People	2 People/People
Avg Daily Labor Force Per Staff	1 days/days	1 days/days	1 days/days
Trainers per New Labor Force	0.2 days/days	0.2 days/days	0.2 days/days
Initial Perceived Trend	0 /days	0.15 /days	0/days

Table 2c Parameter estimates for the Human Resource Subsystem – Productivity Sector

Parameter	Engineering Phase		
	System Engineering	Engineering for Procurement	Area Engineering
Reference Potential Productivity of Experienced Employees	1 Tasks/People-days	1 Tasks/People-days	1 Tasks/People-days
Reference Potential Productivity of Transferred-In Company Employees	0.8 Tasks/People-days	0.8 Tasks/People-days	0.8 Tasks/People-days
Reference Potential Productivity of New Employees	0.5 Tasks/People-days	0.5 Tasks/People-days	0.5 Tasks/People-days
Reference Potential Productivity of Experienced Hire-In Externally	1 Tasks/People-days	1 Tasks/People-days	1 Tasks/People-days
Reference Potential Productivity of New Hire-In Externally	0.8 Tasks/People-days	0.8 Tasks/People-days	0.8 Tasks/People-days
Ref Regular Processing Productivity	0.88 Tasks/People-days	0.88 Tasks/People-days	0.88 Tasks/People-days
Ref Rework Productivity	1.5 Tasks/People-days	1.5 Tasks/People-days	1.5 Tasks/People-days
Ref Quality Assurance Productivity	10 Tasks/People-days	10 Tasks/People-days	10 Tasks/People-days

Table 3 Parameter estimates for the Target subsystem

Parameter	Engineering Phase		
	System Engineering	Engineering for Procurement	Area Engineering
Initial Internal Deadline	187 days	187 days	187 days
Maximum Internal Deadline Extension Dates	40 days	40 days	40 days
Initial Project Deadline for the Phase	712 days	712 days	712 days
Maximum Project Deadline Extension Dates	0 days	0 days	0 days
Initial Quality Goal	0.9 Unitless	0.9 Unitless	0.9 Unitless
Experienced Employee Avg Hourly Pay Rate	650NOK	650NOK	650NOK
Transferred-In Company Employees Avg Hourly Pay Rate	500NOK	500NOK	500NOK
New Employees Avg Hourly Pay Rate	400NOK	400NOK	400NOK
Experienced Hired-In Externally Avg Hourly Pay Rate	800NOK	800NOK	800NOK
New Hired-In Externally Avg Hourly Pay Rate	500NOK	500NOK	500NOK
Avg Hourly Overtime Pay Rate	1000NOK	1000NOK	1000NOK

Table 4 Parameter estimates for the Scope Subsystem

Parameter	Engineering Phase		
	System Engineering	Engineering for Procurement	Area Engineering
Initial Phase Scope	8186 Tasks	2651 Tasks	13 439 Tasks

Table 5. Schedule Pressure Tolerance – Its value is the same for all the three phases

Schedule Pressure	1	1.1	1.15	1.2	1.3
Tolerance level	No limit	9 months	6 months	1.5 month	5 days

Precedence relations in System Engineering phase

Internal_Precedence_Relation = GRAPH (Fraction_of_Tasks_Perceived_Completed)

GRAPH (Fraction_of_Tasks_Perceived_Completed) =

(0.00, 0.026), (0.1, 0.17), (0.2, 0.376), (0.3, 0.573), (0.4, 0.658), (0.5, 0.796), (0.6, 0.868), (0.7, 0.91), (0.8, 0.953), (0.9, 0.986), (1.00, 1.00)

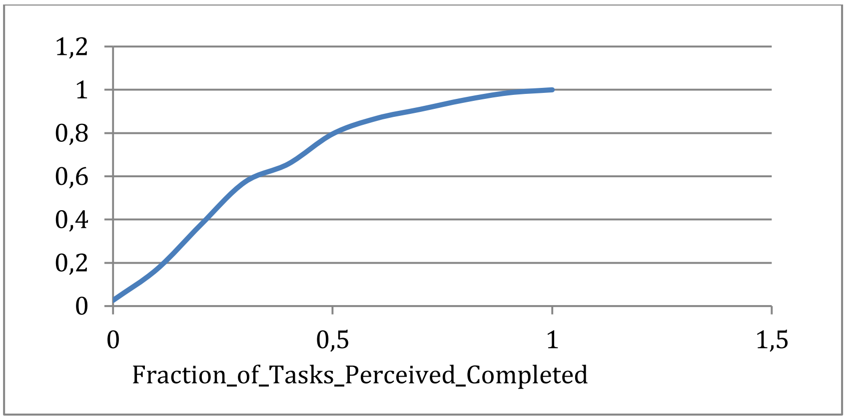


Figure 1. Internal Precedence relations in System Engineering

External_Precedence_from_Up_stream = 1

External_Precedence_from_Down_stream =
GRAPH (Fraction_of_Released_Tasks_from_Downstream)

GRAPH (Fraction_of_Released_Tasks_from_Downstream) = (0.475, 0.7), (0.6, 0.85), (0.7, 1.00)

Precedence relations in Engineering for Procurement phase

Internal_Precedence_Relation = GRAPH (Fraction_of_Tasks_Perceived_Completed)

GRAPH (Fraction_of_Tasks_Perceived_Completed) =
(0.00, 0.042), (0.1, 0.241), (0.2, 0.457), (0.3, 0.628), (0.4, 0.753), (0.5, 0.846), (0.6, 0.904), (0.7, 0.94), (0.8, 0.972), (0.9, 0.994), (1.00, 1.00)

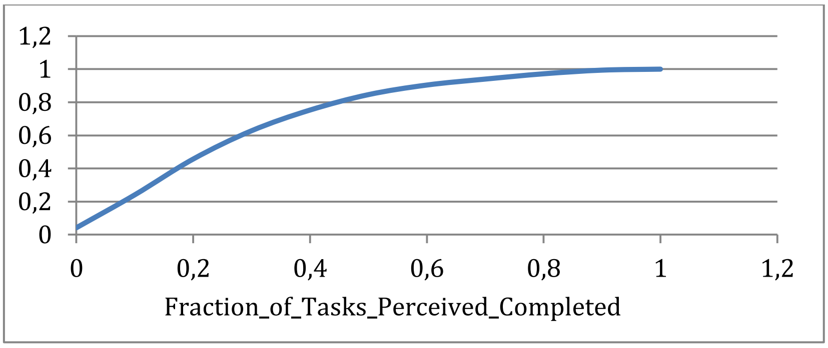


Figure 2. Internal Precedence relations in Engineering for Procurement

External_Precedence_from_Up_stream = GRAPH (System_Engineering.Fraction_of_Released_Tasks)

GRAPH (System_Engineering.Fraction_of_Released_Tasks) =
(0.2, 0.254), (0.376, 0.457), (0.573, 0.628), (0.658, 0.753), (0.796, 0.846), (0.868, 0.904), (0.91, 0.94), (0.953, 0.972), (0.986, 0.994), (1.00, 1.00)

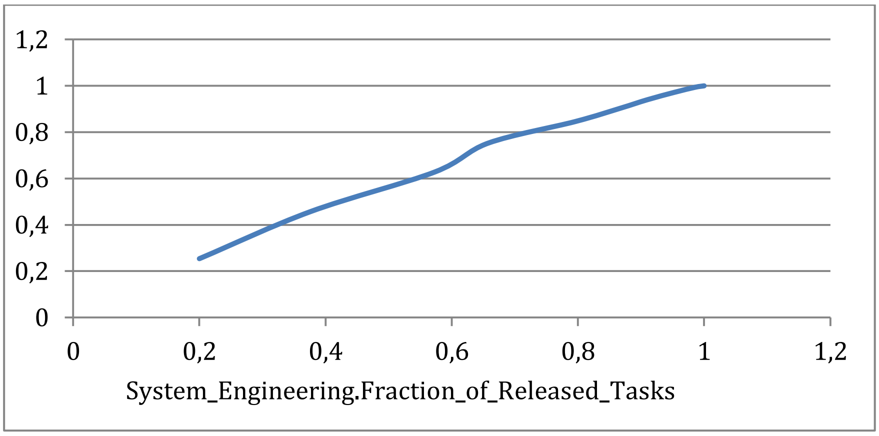


Figure 3. External Precedence relations with upstream in Engineering for Procurement

External_Precedence_from_Down_stream =
GRAPH (Fraction_of_Released_Tasks_from_Downstream)

GRAPH(Fraction_of_Released_Tasks_from_Downstream) = (0.15, 0.475), (0.7, 1.00)

Precedence relations in Area Engineering phase

Internal_Precedence_Relation = GRAPH (Fraction_of_Tasks_Perceived_Completed)

GRAPH (Fraction_of_Tasks_Perceived_Completed) =

(0.00, 0.034), (0.1, 0.208), (0.2, 0.421), (0.3, 0.583), (0.4, 0.675), (0.5, 0.788), (0.6, 0.852), (0.7, 0.899), (0.8, 0.941), (0.9, 0.98), (1.00, 1.00)

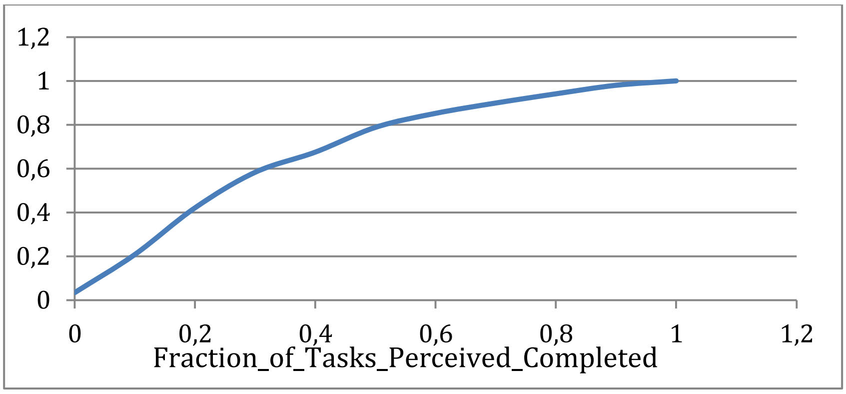


Figure 4. Internal Precedence relations in Area Engineering

External_Precedence_from_Up_stream =

GRAPH(Engineering_For_Procurement.Fraction_of_Released_Tasks)

GRAPH (Engineering_For_Procurement.Fraction_of_Released_Tasks =

(0.241, 0.208), (0.457, 0.421), (0.628, 0.583), (0.753, 0.7), (0.846, 0.82), (0.904, 0.852), (0.94, 0.899), (0.972, 0.941), (0.994, 0.98), (1.00, 1.00)

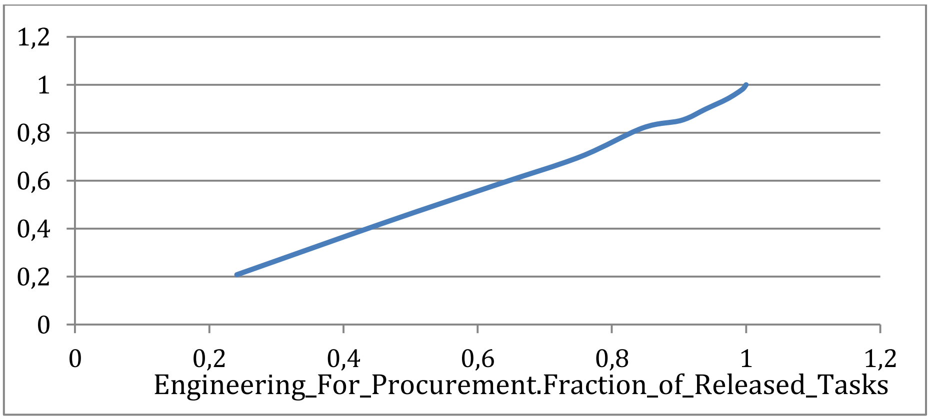


Figure 5. External Precedence relations with upstream in Engineering for Procurement

External_Precedence_from_Down_stream = 1