USING SYSTEM DYNAMICS SIMULATION FOR ANALYSIS OF UNCERTAINTIES IN ENGINEERING PROJECTS

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ABSTRACT

Reducing the development time of new products is a key driver of success in most of today businesses. Concurrent engineering has become a common strategy in the companies aiming for introducing new products faster. However in high-technology companies the new product development is a difficult task because of many different uncertainties existing in such environments. Therefore concurrent engineering of new product development projects should considerably plan for suitable strategies concerning project uncertainties. This research is aiming to quantitatively analyse uncertainties in concurrent engineering of new product development (NPD) projects using a computer simulation approach. The approach is innovative both in technique and application. The simulation technique used for this research is a combined system dynamics and discrete event simulation and the research is empirically analysing a real product development project in a world class manufacturing company. The research results will contribute to better understanding of uncertainties in concurrent engineering as well as testing a method which would help practitioners and researchers in better analysis of uncertainties in projects.

INTRODUCTION

Fast delivery of projects is very important for profitability and success of companies in manufacturing industry. This puts pressure on project managers to further reduce the project delivery time. One common compression strategy is overlapping the activities which normally should run sequentially. This strategy is known as concurrent engineering. Although concurrent development processes can theoretically help any project to finish faster, there are factors like inadequate communication(Adler 1995) and unreliability of preliminary information exchanges(Terwiesch, Loch et al. 2002), which can hamper an effective implementation of the overlapped approach. Acknowledging the numerous decisions required to be taken in any new product development(Krishnan and Ulrich 2001) the importance of decision making in concurrent engineering is evident.

These decisions including how much to overlap activities, when to exchange preliminary information from one activity to another and many more are difficult and complicated decisions for managers. A large part of reasons for this difficulty is because of inherited uncertainties in projects(Dvir and Lechler 2004; Eckert, Clarkson et al. 2004) which by activity overlapping their effects are enhanced. Therefore, development of concepts and methods to help project managers for decision making under uncertainty is very important and essential.

Although numerous research has been published on concurrent engineering, only a few of them have concentrated on analysing concurrent engineering in the micro level of analysis(Krishnan 1996; Krishnan, Eppinger et al. 1997; Terwiesch, Loch et al. 2002; Bhuiyan, Gerwin et al. 2004). Existing research has analysed the relationships of product development time and utilization of resources under different activity overlapping strategies and information sharing regimes(Bhuiyan, Gerwin et al. 2004), trade-offs that arise in earlier or later commitment of one party to the actions of the other parties(Terwiesch, Loch et al. 2002) and decision making for overlapping amount based on the evolution of upstream activities and sensitivity of downstream activites(Krishnan, Eppinger et al. 1997). However many other decisions during product development(Krishnan and Ulrich 2001) relevant to activity concurrency are not sufficiently researched yet. Most importantly no previous research has explicitly analysed the relevant decisions mentioned above in respect to project uncertainty. This work is aiming to quantitatively research optimum decision making in

concurrent engineering while all major sources of uncertainties are taken into account. This optimization concerns both the optimization of the expected and dispersion of the parameters interested in this research(Taguchi 1986). Specially the dispersion of the project performance are important since this could even be a more important metric than expected value for decision making in some projects(Chapman and Ward 2004). With this definition of objective one would consider this research within the area known as project risk analysis. However the traditional risk analysis methods are not sufficient to capture the complexity, non linearity and soft effects existing in projects(Sterman 1992; Williams 2005). System Dynamics is the method which can be used to analyse systems considering the effects mentioned above(Forrester 1961; Sterman 2000).
System Dynamics has been applied to project management since 1964 to analyse different resource allocation policies(Roberts 1964; Roberts 1974), counter-productivity of adding resources late in the projects(Abdel-Hamid and Madnick 1991), supporting delay and disruption claim for some major projects in ship-building (Cooper 1980) and rail wagon manufacturing(Williams, Eden et al. 1995; Ackermann, Eden et al. 1997; Eden, Williams et al. 1998), analysing the effect of "error and rework hiding" in concurrent engineering(Ford and Sterman 2003) and the effect of change and rework in construction projects(Love 2002; Park and Pena-Mora 2003; Love, Irani et al. 2004).

Generally the previous researches in Project Management using System Dynamics were seeking to find conditions and circumstances under which projects could run faster and more efficient. In other words they were aiming to find or analyse conditions of optimality. However the significance of disturbances and uncertainties in project environments necessitates incorporation of stochastic modelling into the system dynamics models which is not observable in any of the previous research. The reason for neglecting stochastic modelling could be because of three reasons: Firstly, the analysis of uncertainty were not in focus or there were not interest in it at the time, secondly; the technical capability to incorporate stochastic processes within the SD models is a recent capability in the softwares and thirdly; there has not been much work on this issue even in the main stream system dynamics research which could be attributed to the fact that traditionally stochastic simulation considered a different paradigm within discrete event simulation(Law and Kelton 2000).

This research is using System Dynamics in an innovative manner to analyse uncertainties in concurrent engineering projects. This is a novel method in project uncertainty management. While acknowledging that the technical possibility is to the credit of the selected software, the innovation in application and in addressing the concerned managerial issue is unique to this research. The research is having a case study research strategy and can be best described as an attempt to answer the following research question:

"What is the best concurrency strategy in the case study in regard to both mean and dispersion of possible project performance when the effects of uncertainties are enhanced due to overlapping of phases?"

In addition, this research tests the following proposition:

"In SD, modelling disruptions and changes in the process model of NDP projects through quantifying the parameters with stochastic processes is a better modelling practice and gives more reliable simulation results."

Every project is unique and need to be analysed within its own context(Dvir, Shenhar et al. 2003; Engwall 2003). Consequently the suitability of every modelling method depends on the objective of the modelling and the case where modelling is applied. Therefore this research does not seek to provide evidence on the general suitability of the selected analysis method for every project. However this research has found the selected method suitable for analysis of decision making and management of uncertainties in concurrent engineering at the selected NDP case study.

In addition to the managerial insights which expected to be gained through analysing simulation results of the case study, the success of the selected method in this research to answer the research questions, will indicate the empirical validity, practicality and usefulness of the selected method for the first time in a case study and would open new frontiers in project management and system dynamics research.

RESEARCH STRATEGY

The research strategy in this research is a single case study(Yin 1994) within the product development organization of a world class manufacturing company. The research is aiming to understand the dynamics and the processes which are present within the case study(Eisenhardt 1989) through the data collection

methods. Thereafter this data will be linked to the simulation model for quantitative analysis(Yin 1981).
Data collection in this research will involve face-to-face interviews with project managers and senior design engineers, as well as reviewing secondary data sources like reports which are produced for other purposes. In this research both semi-structured and unstructured interview styles will be used. Usually within the selected company some unstructured interview will be done to get a general understanding of the issues and the state of affairs within the projects and then some semi-structured interviews will be conducted to exploit soft and hard data necessary for modelling and simulation.
At this stage of the research no more description of the case study is authorised due to confidentiality matters.

MODEL DEVELOPMENT

Although enough empirical data is not collected to completely develop the model representing the environment of the case study, a basic mock up model representing a simple concurrency of phases in hypothetical project is already built. The components within this model are based on the intuition from my previous experiences, the literature and the current available information about the case study. There are some advantages for working with this model. First, issues and problem regarding the technical difficulties of the innovative modelling approach in this research will be revealed early in this research. Second, gradual improvement of the model as the empirical data of the research accumulates helps to sharpen the interview agendas to the information required by the research.

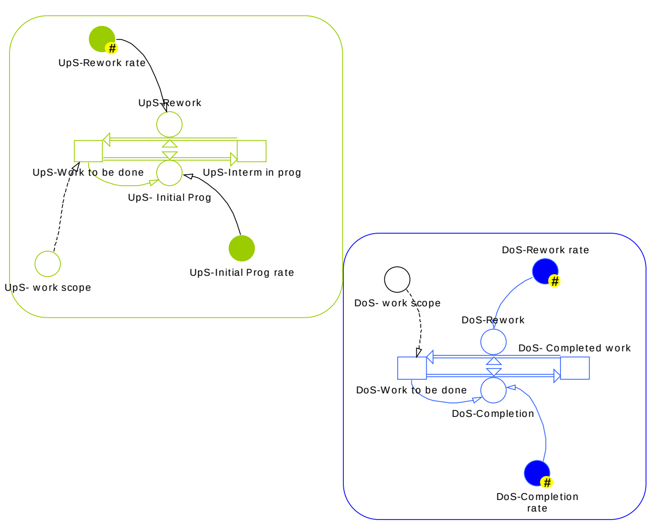

***Figure 1**.The simplified structure of the model*

The current model is actually a fast changing model since my available data and my detailed modelling approach is changing continuously. However I believe explaining some discrete aspects of the model would give some more insights about this research. Figure 1 shows the fundamental stocks and flows of the model. Each square encompass the elements specific to the upstream or downstream task completion mechanism. The auxiliary variables filled with colours are the variables which are fundamental in determining the progress, rework or iteration of each of the two phases. These variables and the other variables which would interact with them are defined in other parts of the model. For example in one part of the model the rework rate of the upstream phase is defined as event which would occur discretely during the simulation with a randomly generated time between each event which has statistically a negative exponential distribution. Figure 2 indicates the random numbers which are generated for this event in one iteration of the simulation.

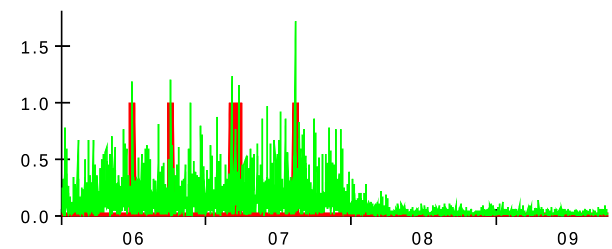

***Figure 2**.Stochastic generation of random variable for the time between two consequent changes in the upstream based on a negative-exponential distribution*

Based on the structure defined in the model and the random occurrence of the stochastic parameters the progress of the upstream and downstream phases as a progress percentage may indicate different patterns in different simulation runs. Figure3 indicates one possible form of how the upstream and downstream phases in this hypothetical project would progress. It should be mentioned that in this hypothetical project it is assumed that there is a limit at each point of time for the progress of the downstream tasks. This limit is actually calculated based on how much information is available from upstream. This limit is indicated by the second curve in Figure3. Actually this is one of the managerial decisions which require proper decision making regarding how close the downstream progress should get to this limit. There are many other managerial decisions like:

- Assignment and levelling of resources
- trade off between the quality, innovation and project cost and duration
- the decision on using or not using uncertain information

- the decision on how to use uncertain information
- decision on when to freeze design
- decision on how to release the phase deliverables; batch, continuous, frozen, unfreeze, etc
- The communication decisions like: when and to whom should teams report, frequency, delays, etc
- Decisions regarding the acceptance or rejection of change requests
- Contingencies

These decisions will be explored and refined during the empirical investigations to define the scenarios or strategies which will be analysed in the simulation. At this stage of research I can not exactly define what would be the different strategies which will be tested with the simulation model since there is not enough empirical data yet.

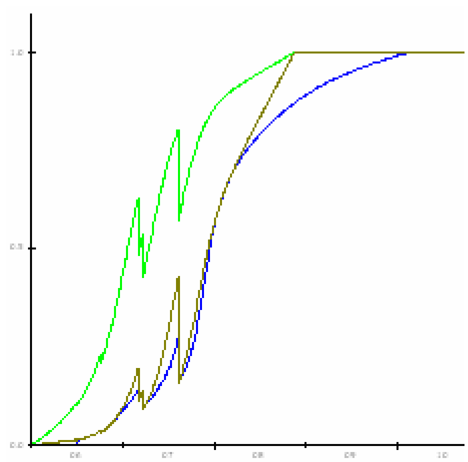

Figure3.*An example iteration of the model output indicating upstream progress (the most upper curve), possible progress for downstream (the curve in the middle) and the downstream progress (the most lower curve)*

As indicated in Figure3, the significance of the disturbance in the progress of the phases is high. The project completes under disturbances before being able to demonstrate any consistent behavioural pattern like goal seeking or oscillation(Sterman 2000). This is actually in accordance to how this research perceive the product development projects(this needs to be approved by the empirical findings). So while such high impact disturbances are present in the NDP projects one run of the simulation would not necessarily indicate all possible patterns of progress and disruption a project may go through. Therefore this research analyse the results not through one simulation iteration, but through statistically analysing a large number of the simulation iterations which are presumably different from each other; because of the randomness in the stochastic parameters in the model. This is a common approach in analysis of Discrete Event Simulation results(Law and Kelton 2000) but it is a new approach in analysis of SD simulation outputs and makes it possible to analysis dispersion of the simulation results (refer to the research question).

VALIDATION

One of the main problems in simulation studies is to determine whether a simulation model is an accurate representation of the real system under study or not. This task is generally called validation. Through validation, the confidence level is increased that an inference about the simulated process is correct for the actual process as well(Van Horn 1971). In this research the validation of the model is not planned to be done in one stage after the completion of the model, instead validation is considered a parallel task to model development and is continuously examined with empirical data(Balci 1994). Knowing that complete validation of a model is impossible(Sterman 2000 p.846), several aspects of model validity and related techniques are mentioned in the literature(Sargent 1979; Barlas 1989; Balci 1994; Law and Kelton 2000; Sterman 2000; Burton 2003; Banks, Carson et al. 2005) which the ones that are relevant to this research will be discussed here.

Validation of the *model assumptions* is an important aspect of model validation which requires the testing of the assumptions about the structure of the model and the assumptions about the data used for calibration(Van Horn 1971; Banks, Carson et al. 2005). The structural validity will be examined using *face validity* test while the validity of the calibration data will be tested by using different statistical techniques(Kleijnen 1995). *Face validity* is about asking people knowledgeable about the system whether the system is reasonable(Sargent 1979; Banks, Carson et al. 2005). Since building the model in this research is done in parallel with empirical data collection (interviewing); in the interview meetings the model will be discussed with the interviewees asking for their evaluation of the model. The confirmation of the interviews who are the experts in the subject increases the face validity of the model(Naylor and Finger 1967; Law and Kelton 2000). In addition, during the model development the model will be checked with the *existing theory* and the results from *similar simulation studies* to check the similarities or discrepancies between the model and the previous validated theories and simulation studies(Law and Kelton 2000).

The other aspect of validity which is important especially in System Dynamics models is the *behavioural validity*. Behaviour validity tests if the model is capable of producing acceptable output behaviour(Barlas 1989). Calibration can be helpful for this purpose(Oliva 2003). Calibration can be used to iteratively compare the model to the real system , making adjustment to the model, comparing the revised model to reality, making additional adjustment and comparing again (Banks, Carson et al. 2005). Calibration of the computer models can be enhanced using different data sets to test if the model shows the same behaviour. *Boundary Adequacy* is also important in the validity of the System Dynamics models. A boundary adequacy test assesses the appropriateness of the model boundary for the purpose at hand(Sterman 2000 p.861). To test the adequacy of the model boundary, constants within the model which actually represent exogenous factors, should be checked if they are really constant or they can possibility be considered as variables in the model. Also the model should be checked if any feedback loop or model component is omitted.

FUTURE RESEARCH

This research is an ongoing research and currently data is being collected to further develop and calibrate the model discussed here. However the issues and the research questions mentioned in this paper are sufficient to indicate a new direction of research using system dynamics simulation. Other researchers can adapt the approach selected here to analyse other type of projects. This will establish the application of system dynamics as a new analysis tool for better management of uncertainties (including risks) in engineering projects.

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