

Simulation of a Distributed Design Project

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Abstract

Dissemination of system dynamics to project management practitioners is not as widespread as its use for project management theory building within the system dynamics community. This article presents a decision support and training project model built for a global consulting and engineering company. The simulation model comprises the most important work phases within the detail engineering phase of a large investment project in three offices. The model was validated using data from several past projects and in workshops with the company. A user interface was built to aid dissemination and use of the model. The purpose of the model is the bottleneck analysis and simulation of an ongoing engineering project, as well as the simulation of quality, scheduling, and profitability issues when outsourcing parts of the detail plant engineering.

Keywords: distributed project, system dynamics, simulation, decision support, design service

Introduction

Projects have many interdependent components making them dynamically complex. In addition to the numerous work phases performed internally, supplier and customer information has to be managed as well. System dynamics models of project work are typically based on some form of the “rework cycle” (Cooper 1980, Abdel-Hamid 1984, Ford & Sterman 1998) in which errors in project work generate rework slowing down progress. These models also include feedbacks and unintended consequences from managerial decision making, such as changes in personnel resources, overtime and faster

work, deadline changes, and managerial forecasting of performance. While system dynamics has been widely and successfully used to model project work, there is still much work to be done in disseminating theory built using system dynamics to project management practitioners. (Lyneis & Ford 2007).

The propagation of errors between work phases (Ford & Sterman 1998) and the distinction between rework due to errors and due to external change requests (Park & Peña-Mora 2003) have been presented in the system dynamics literature. In this paper, we distinguish between three types of rework: errors generated in a particular work phase, errors inherited from upstream work phases, and change requests because of quality problems in the external purchase process. We find this categorization useful in pinpointing the causes of problems in particular work phases. This distinction is important because of the fundamental attribution error: it is helpful to show that the reason for rework is in the process, not in employees working on a particular work phase.

Dividing work into various offices around the world has many benefits, such as work load balancing and the ability to use cost effective resources and local know-how. However, geographical distances between offices slow down communication because of slow data connections and time differences. Information delays due to slow data connections vary between few hours to weeks, and information delays due to time differences depend on the direction of information flow. Employees from different cultures also behave differently, which needs to be considered in distributed projects. For example, cultures differ in the degree employees make independent decisions without supervisor guidance and how they evaluate tradeoffs between schedules and work quality.

While these issues are important, to our knowledge they have not been addressed in the system dynamics literature. In this paper, we model employee differences in different offices by taking into account different experience levels, productivities, work qualities when prerequisite information is not available, and price levels. We also model the effect of distributed work to employee productivities.

Problem definition and scope

This article presents a system dynamics simulation model done for Pöyry, a global consulting and engineering company focusing on the energy, industry, urban & mobility, water & environment, and management consulting sectors, with operations in 50 countries. The company is interested in developing project management support tools for large distributed investment projects. The purpose is to use the model in the bottleneck analysis and simulation of an ongoing engineering project, as well as in the simulation of quality, scheduling, and profitability issues when outsourcing parts of the detail plant engineering.

The focus of the model is in the detail engineering phase of an investment project preceding the construction phase. The scope of the model is one project and the time horizon approximately two years. In the beginning of a project, a start-up date for a factory plant is set. This date is fixed, and must not depend on how well the planning and construction phases are implemented.

Insufficient data being the most common cause for errors and incompatibilities in design, one aim for the simulation model is to show the effects of delayed customer and supplier data. It is common for Pöyry's clients and suppliers to underestimate the effects of small changes which can cause dramatic effects to the whole project, including large costs in the construction phase. The simulation model can also be used for pricing change orders in the future.

Six engineering disciplines are included in the model: process, instructions and standards, mechanical, piping, electrical, and automation. The process design phase, which includes procurement services affecting the client's purchase process, is the first part in detail engineering and provides base information for all other disciplines. Each discipline is divided into 2-5 sub disciplines constituting 22 individual work phases, and the workforce is divided along the engineering disciplines. In real life there are still many more disciplines and work phases in a typical project. For example, one real project had 22 main disciplines and a total of 184 sub disciplines. The scheduled start and end of each work phase are based on real projects. The final deadline of the whole project is kept constant, but deadlines of individual work phases can be postponed if there is too much schedule pressure.

In the model, work hour costs of the different engineering disciplines constitute the costs of the project. Work hour price levels depend on the engineering discipline, office, and the overall experience of the employees. A normal work week is assumed to consist of 40 work hours, and overtime hours are assumed to cost the same as normal work hours. The purchase process and supplier data acquisition are assumed to generate no work costs. Workers generate costs as long as they are resourced to the project, i.e. until a particular workforce discipline at a particular office has finished its work.

Work phases and workforce

The amount of work in each work phase is estimated based on the number of deliverables, such as the number of documents or database entries. The work units depend on the engineering discipline. Pöyry has adopted several Key Performance Indicators (KPIs) to measure productivities in different engineering disciplines and sub disciplines, and KPI values have been measured in earlier projects. The KPI values describe the number of hours required to finish one unit of work and depend on the discipline, overall experience of workers, and the office to which a work phase is assigned. The estimated number of workers needed for a particular work phase can be calculated based on the amount of work, KPIs, and project scheduling.

The required work rate for a particular discipline at an office depends on the ratio of work left and time remaining to the deadline. The required workforce, which is calculated based on the required work rate and estimated productivities, influences worker allocation to the project. The use of overtime work is dependent on the required work rate, normal work rate, and the available workforce, and can change more rapidly than the workforce.

Workers in each discipline are assumed to be able to work on all sub disciplines within a discipline, but not on sub disciplines outside the discipline. Worker experience is modelled along two dimensions: overall experience and project experience. Both dimensions can

have three values: novice, intermediate, or expert. Overall experience refers to the general competence level that accumulates through multiple projects, and stays constant throughout the simulation that encompasses only one project. The project experience of workers on the other hand changes throughout the simulation. Since all projects are somewhat different, even overall experts need some time to adjust to the intricacies of a new project. This is why the project experience of all workers is set to novice at the start of the simulation. Also, if new workers join the project at a later time, they begin as project novices. As time progresses, workers become project intermediates and project experts. The higher the overall experience level of the workers, the faster this progression is.

Project novices and intermediates need guidance from experts. This lowers the amount of time experts can use to their actual work, effectively lowering their productivities. Intermediate employees can help novices in simple tasks, but the final decisions are made by the experts because of their higher knowledge. Overall, the workforce model (Figure 1) has similarities with Oliva & Sterman's (2010) experience chain and learning curve model.

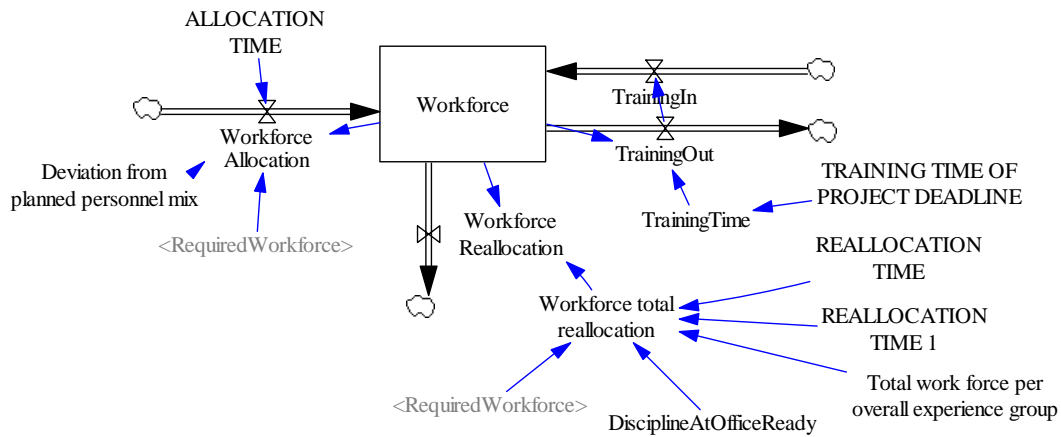


Figure 1 Workforce

Each office is assumed to have a fixed proportion of the overall experience groups, as well as a fixed number of total available employees in each discipline during the course of one project. Employee productivities as well as abilities to work based on incomplete prerequisite information differ significantly.

Work rates

Workers are allocated to individual work phases based on the required work rate (work units/week) of a particular phase. The required work rate is the ratio of active work in a phase (i.e. not completed work that is scheduled to start) and the time left until deadline. The workforce can be allocated entirely to the task with the highest required work rate, proportionally to different phases based on their respective required work rates, or as a weighted average of the highest priority task and proportional allocation. To model delays in the allocation process, exponential smoothing is used to obtain the actual allocation.

The work rate (work units/week) of a particular phase depends on the number of employees allocated to the work phase and their productivities. The productivity of novices is lower than that of experts, and novices also require expert guidance which takes experts' time away from actual work. The use of overtime can increase work rate on the short run, but prolonged overtime decreases productivity. The communication delay within distributed projects is also included in the model. The work rate is lower when the proportion of prerequisites done in other offices is higher.

Figure 2 shows the work rate of two sub disciplines, M40 and M50, and how the allocation of workers to each phase changes throughout the simulation.

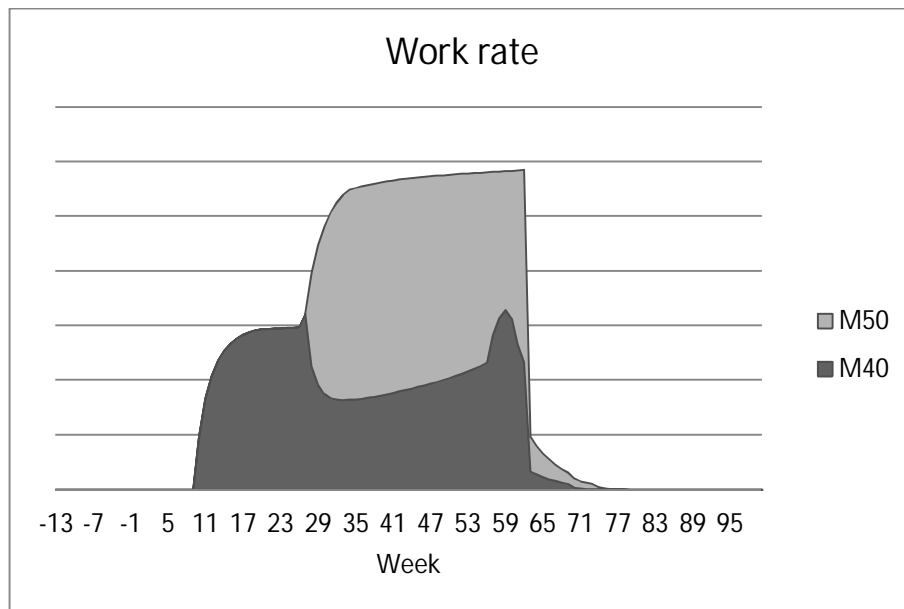


Figure 2 Work rate for two work phases

Task concurrence and prerequisites

Prerequisites refer to data and work phases that must be sufficiently completed to proceed in a further work phase. Prerequisites between phases are modelled using three "prerequisite matrixes" (Figure 3): the limit 0%, limit 50%, and limit 100% matrixes. The limit 0% matrix defines the proportion of preceding phases that needs to be completed to start the following phase. The limit 50% and limit 100% matrixes define the proportion of work that needs to be finished to complete half and completely finish the following phase, respectively. As such, the prerequisite matrixes are similar to design structure matrixes.

		Prerequisite phases (j)																
		Internal work phases				Purchase process phases				Supplier data acquisition								
		1	2	...	n	1	2	...	n	1	2	...	n					
Phase (i)	Internal work phases	1																
		2	x												x			
		...	x	x											x	x	x	
		n		x	x										x			x
	Purchase process phases	1	x	x	x													
		2					x											
		...		x			x											
		n					x											
	Supplier data acquisition	1					x											
		2					x											
		...					x	x										
		n					x	x										x

Figure 3 Prerequisite matrix

To calculate the possible completion of a following phase, piecewise linear functions are used to interpolate between the three values defined by the prerequisite matrixes (Figure 4). If a phase has multiple prerequisites, the possible completion for the following phase is the minimum of individual limits. The shapes of the prerequisite limit functions are different. Sometimes all the data is required already in the beginning of the work phase; sometimes only a small part of it is required immediately and the majority only at the end. Ford & Sterman (1998) have used a similar approach to model prerequisites in product development. The main difference in our approach is the use of prerequisite matrixes to handle numerous prerequisites and to generate the prerequisite functions.

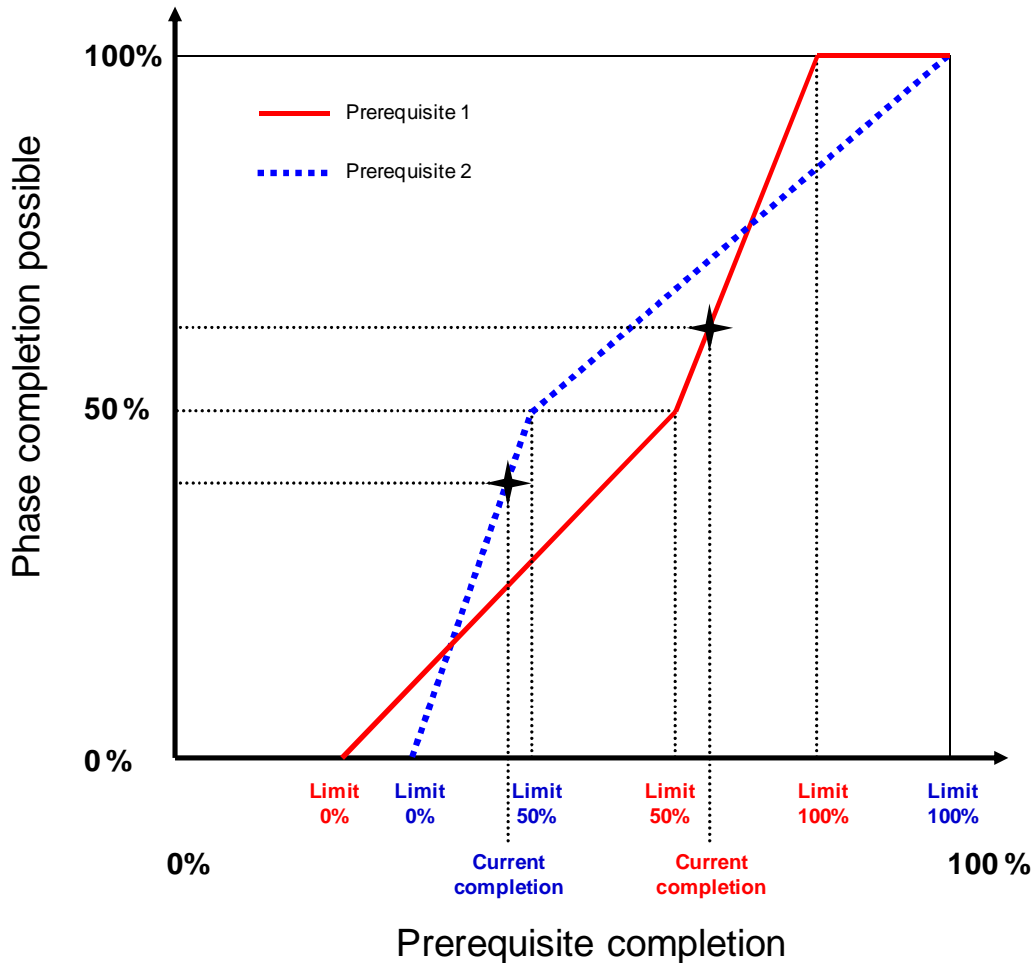


Figure 4 Prerequisite function

Purchase process and supplier data acquisition

The quality and timeliness of the purchase process and supplier data, which influence work phases dependent on supplier data, depend on the competencies of the suppliers and the client. The purchase process is assumed to start as scheduled. Supplier data acquisition follows the purchase process with a delay, after the prerequisites defined in the prerequisite matrixes have been met.

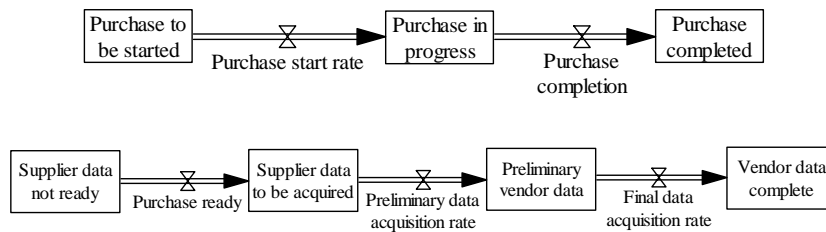


Figure 5 Purchase process and supplier data acquisition

Clients and suppliers have a rating in Pöyry’s system. The closer the partner’s working culture is to Pöyry’s, the smoother the communication. A long common history of working together makes collaboration easier.

After a client decides to order a certain part from a supplier, the supplier is required to deliver preliminary data in approximately a week. The preliminary data are usually based on a similar earlier project and are not totally accurate, but can be used to begin design work. The final data are delivered in a few months. The supplier’s know-how and experience affect the amount of deviations delivered within the data, the general precision of the data, and their timeliness.

Errors and rework

A rework cycle where different work phases are modelled using arrays (Vensim® subscripts) is used in the model (Figure 6). In the model, errors are grouped into three categories: errors generated in a particular work phase, errors propagated from other work phases, and errors resulting from the purchase process. It is normal to have some errors generated in work phases, but the use of overtime and by the lack of prerequisite information increase the number of errors.

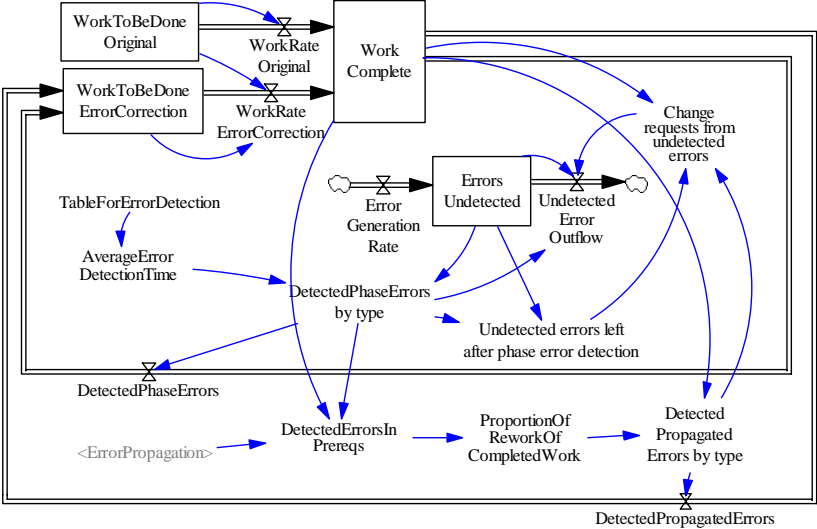


Figure 6 Rework cycle

The simulation of a complex detail engineering project did not at first yield realistic results using the values in the prerequisite matrixes that were collected. A solution to the problem was found from the real world: when data is not available but engineering needs to progress to keep the schedule, experienced engineers use heuristics, or educated guesses and intuitive judgment. These decisions may prove correct or incorrect when data later become available, depending not only on luck but also on the skill and experience of the engineer. The accuracy of the heuristics increases with experience as engineers are able to use tacit knowledge gained in earlier projects. Heuristic accuracies also depend on the composition of the work team. If there are enough experts in the team, novice workers do not have to

resort to their own less accurate heuristics. Heuristic accuracies also depend on the office due to different working standards and cultures.

Let n_1, n_2, n_3 be the numbers of overall novices, intermediates, and experts in a work team, p_{12} the number of needed intermediates per novice, p_{13} the number of needed experts per novice when enough intermediates are available, p'_{13} the number of needed experts per novice when enough intermediates are not available, and p_{23} the number of needed experts per intermediate worker. The proportion of the different experience groups using different heuristic accuracies is seen in Table 1, where $\alpha_2 = \min\left(1, \frac{n_2}{p_{12}n_1}\right)$ is the proportion of novices with enough intermediate guidance and $\alpha_3 = \min\left(1, \frac{n_3}{n_1(p_{13}\alpha_2 + p'_{13}(1-\alpha_2)) + n_2p_{23}}\right)$ is the proportion of novices and intermediates with enough expert guidance.

Table 1 Heuristic accuracies of workers

	Using novice heuristic	Using intermediate heuristic	Using expert heuristic
Proportion of novices	$1 - \max(\alpha_2, \alpha_3)$	$\max(\alpha_2, \alpha_3) - \alpha_3$	α_3
Proportion of intermediates		$1 - \alpha_3$	α_3
Proportion of experts			1

The number of errors propagated from earlier work phases depends on the proportion of work that has to be redone in the earlier phase as well as the extent the later phase is dependent on the earlier phase, defined in the limit 100% prerequisite matrix.

The number of errors resulting from the purchase process depends on the client's and suppliers' know how. Additional delays in the purchase process that are not taken into account in project scheduling also cause of errors since workers lack information in phases dependent on supplier data. Purchase errors are also propagated to other work phases.

Model validation

Our simulation modelling project team consisted of VTT's system dynamics researchers as well as global discipline leaders from Pöyry's Engineering Centre. An iterative modelling approach was adopted (Sterman 2000). Since Pöyry did not have prior experience in using system dynamics modelling, the first goal was to increase understanding of the benefits and limitations of business process simulation using a hands-on group model building approach to simulation. The team gathered together once or twice a month for 3-4 hours meetings to discuss the simulation model. In between the meetings the researchers refined the model according to requirements from the previous meeting, and Pöyry's team debugged, tested, and commented the model.

The workshop sessions were used to define the model boundary and to validate the structure and behaviour of the model. Many of the generic structures in the model have been published and previously validated in the system dynamics literature, such as the

rework cycle, the effect of overtime to quality and productivity, and the human resource dynamics related to training novice workers (Lyneis & Ford 2007, Oliva & Sterman 2010). Some company specific policies also emerged from the interviews and workshops, such as the use of heuristics when prerequisite information is not available, and these were included in the model. Compared to many existing and published system dynamics models, the model presented in this article is more detailed as it includes 22 different work phases and 3 offices.

We used partial model testing to see how the behaviour of the model changed when some parts of the model (such as error generation and the effect of overtime on quality and productivity) were removed. We also used other standard model validation tests, such as extreme condition and dimensional consistency testing (Sterman 2000).

Data for the simulation model were gathered from Pöyry's past projects. The projects differed in terms of the offices used and delays in supplier and client data. It was useful to obtain data both from successful and less successful projects to be able to include the causes for failures in the model. The model was calibrated to replicate the behaviour of real life projects in different scenarios. Pöyry has previously collected data on many of the parameters in the model, such as the productivities of different employees, amounts of work in different work phases and the timeline of the project. Data regarding other parameters, such as the prerequisite limits between work phases, were not previously available in numeric format. These were either elicited during the simulation workshops or gathered internally by Pöyry in between the meetings by interviewing their domain experts. Much of the data are confidential and are therefore not presented in this article.

The modelling went through multiple iterations during which corrections and additions were made. We used Vensim® to build the simulation model. We also built a MS Excel® user interface from which the model could be run. This allowed easy distribution of the model and user interface to people who did not have experience of system dynamics nor Vensim® installed on their computers. It was very useful that multiple people could test the model by themselves and point out limitations that could then be corrected in the next iteration phase. Also, since it was possible to change model parameters using the Excel® user interface, Pöyry's employees could tune parameters by themselves, making the validation process faster.

User interface and simulation results

From the user interface, the user can select the office for each of the 22 work phases (Figure 7) and test the effects of uncertainties related to the purchase process (Figure 8) to the implementation of the project in different scenarios.

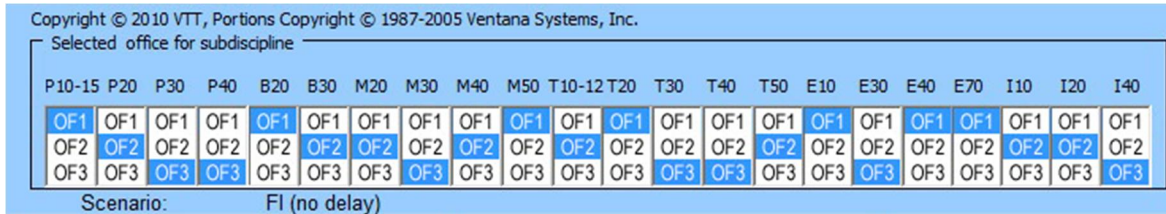


Figure 7 Selection of offices for work phases

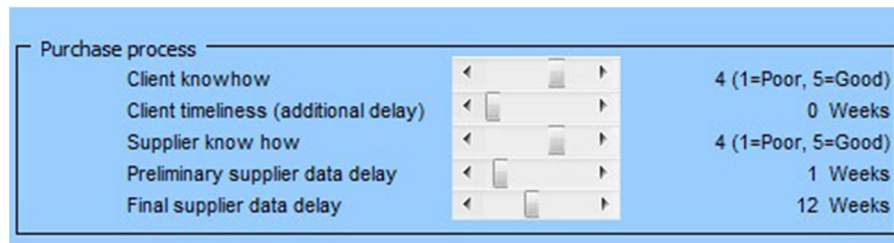


Figure 8 Purchase process uncertainties

Figure 9 shows the simulation results of the following variables:

- Full costs: Engineering disciplines' work hour costs.
- Discipline stage: Proportion of work completed in the engineering disciplines.
- Discipline work hours: Either the work hours as a proportion of planned hours or their absolute values are shown in the user interface.
- Work distribution: Work in the project is categorized into original work, corrective work due to errors in the same work phase, corrective work due to errors in earlier phases, and corrective work due to errors in the purchase process.

Some values are hidden from Figure 9 due to the confidentiality of the data.

Figure 10 shows the work distribution of each individual work phase.

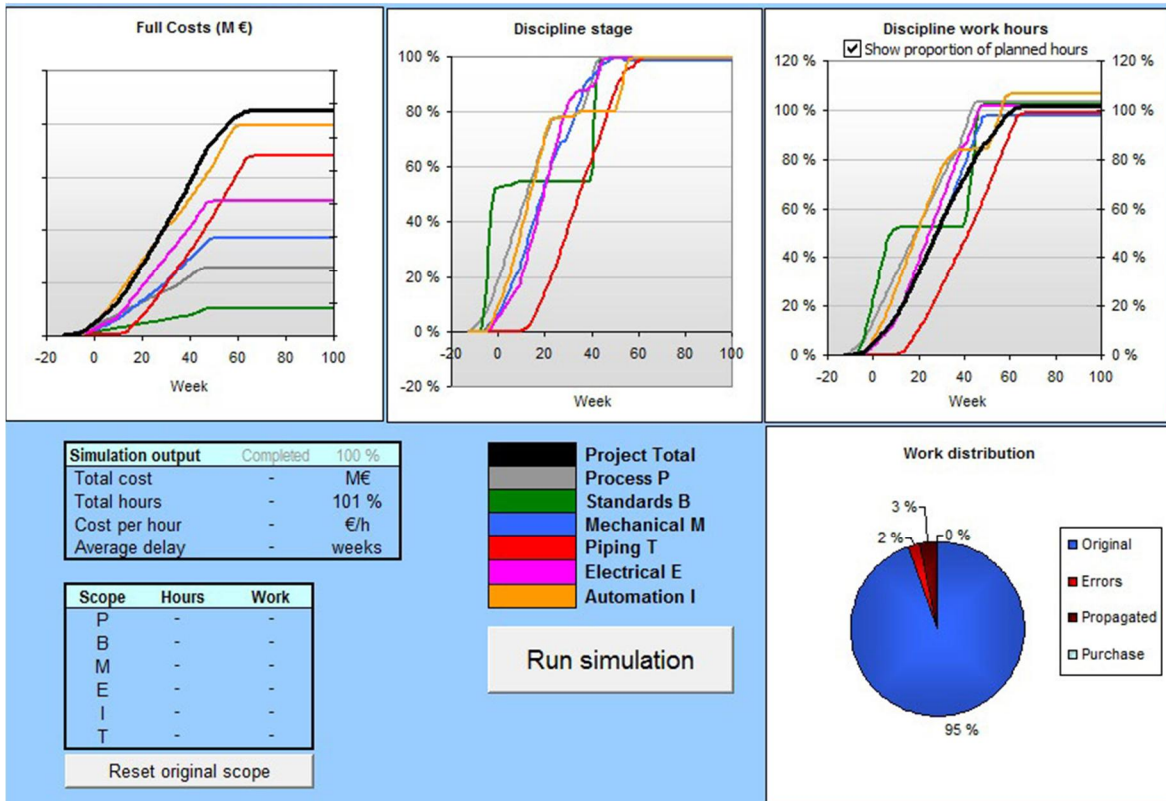


Figure 9 Simulation results: expenses, work progress, work hours, and work distribution

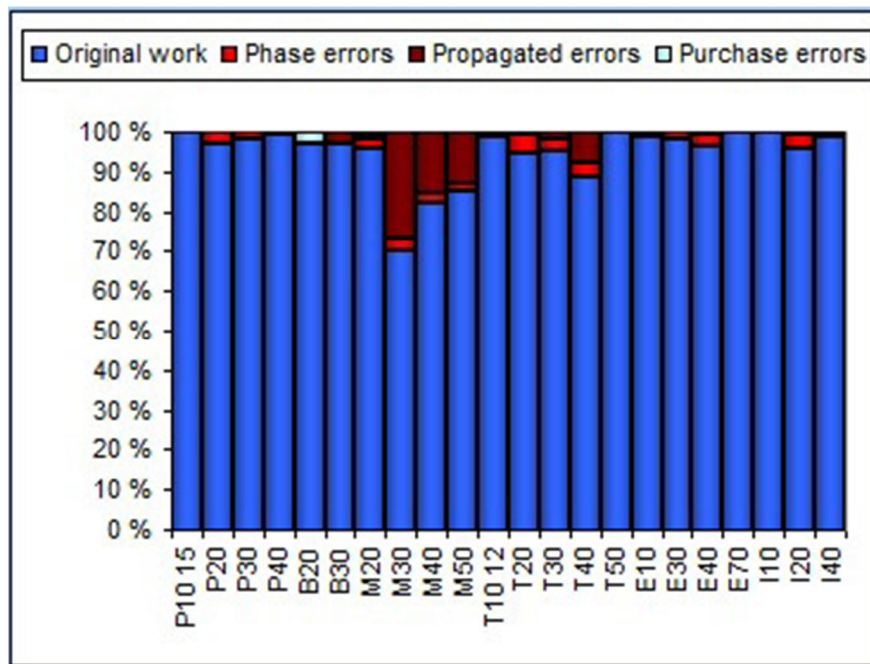


Figure 10 Simulation results: Work distribution of individual work phases

The Excel® user interface allowed Pöyry’s analysts to visualize the simulation results in different formats and use the results for further spreadsheet analyses. For example, Pöyry’s analysts have added a time schedule comparing planned and simulated work hours (Figure 11), where the planned schedule is shown in grey and simulated schedule in green or red, depending on whether the work is completed on time or not.



Figure 11 Time schedule comparison between planned and simulated

We performed a Monte Carlo sensitivity analysis to test the effect of uncertainties in the purchase process to the work hours in the whole project. The model was simulated 1000 times using Latin hypercube sampling for parameters in Table 2.

Table 2 Sensitivity analysis parameters

Parameter	Distribution
Client know how	~ Uniform(1,5)
Client timeliness (additional delay)	~ Uniform(0,12)
Supplier know how	~ Uniform(1,5)
Preliminary supplier data delay	~ Uniform(0,10)
Final supplier data delay	~ Uniform(5,20)

Figure 12 shows the results of the sensitivity analysis. The work hours are shown as a proportion of planned hours.

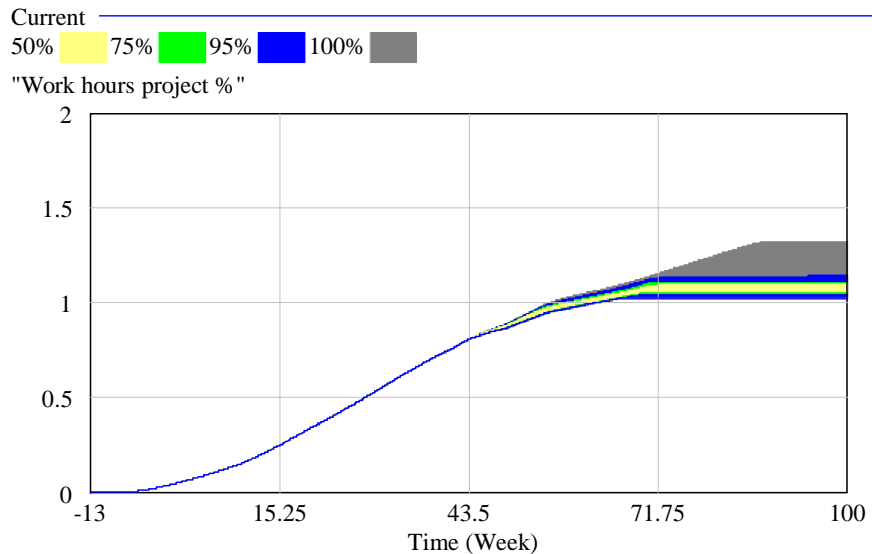


Figure 12 Sensitivity analysis for uncertainties in the purchase process

Discussion and conclusions

The system dynamics model presented in this article is sufficiently detailed to be used in real life project management as a tool to understand the interconnections between internal engineering disciplines, offices, and work phases, as well as external clients and suppliers. Late information from the client or suppliers can be shown to create problems throughout the project. The model can also be used to study the effects of a distributed project implementation to quality, scheduling, and profitability. The model also shows the development of some variables, such as the number of undetected errors, which cannot be measured in real life.

Since cultural differences are an important factor when implementing a project in multiple locations around the world, future work should concentrate on modelling the effects of cultural differences in more detail. Differences in values and norms often cause communication difficulties and misunderstandings regarding work practices when people from different cultures interact. Phillipson & Schlingensiepen (2009) have built on Hofstede's (2001) framework of cultural differences and have used national, personal, and organizational dimensions in predicting potential problems between employees using Bayesian networks. However, this kind of analysis has not to our knowledge been integrated with system dynamics modelling.

Our aim in the future is to use the system dynamics model together with other project management tools to aid decision making in the following areas:

- **Resource optimization in a distributed project:** Finding the best number of employees of different experience groups in different offices to implement a project within a given time frame.
- **Reacting to project changes such as delayed purchases:** With a simulation model, the impact of different policies during an ongoing project can be tested in order to take the best course of action in real life.
- **New clients and suppliers:** Based on Pöyry's experience, the co-operation between new partners can sometimes be very challenging. Simulation modelling can help in doing proper risk analyses in these situations.
- **Finding bottlenecks:** The simulation model can be used to identify critical bottlenecks in project working methods and scheduling.
- **Schedule optimization in a project:** One very useful feature for a complex project would be schedule optimization based on the total cost of engineering or the quality of engineering.
- **Multiple projects:** Pöyry is always working with several simultaneous projects, which may cause difficulties in personnel resourcing. The ultimate goal is to be able to simulate a multi-project situation with external disturbances in one or more projects, and to be able to simulate and optimize the resourcing and scheduling of the projects.

Currently, Vensim® was used to implement the system dynamics model. The aim in the future is to develop the model further using the Simantics System Dynamics software (<http://www.simantics.org>), an open source tool supporting modularity and easy maintainability of complex models (Lempinen et al. 2011).

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