Understanding the Implementation Dynamics of a Technology Intervention Project

Jayendran Venkateswaran[*], **Kelsey Werner**[#], **Chetan S. Solanki**[*], and **Gautam N. Yadama**[#]

[*]Indian Institute of Technology Bombay, Powai, Mumbai 400076, India
jayendran@iitb.ac.in, chetanss@iitb.ac.in

[#]Boston College School of Social Work, Chestnut Hill, MA 02467, U.S.A
Kelsey.werner@bc.edu, yadama@bc.edu

Abstract

This paper presents preliminary work on modeling and understanding the implementation dynamics of a large-scale solar technology intervention project in rural India. The model focuses on project implementation rather than the intervention's impact. The project aimed to provide solar lamps to a million school students by assembling the technology locally at assembly-distribution centers spread across rural India. This involved recruiting and training local people, regular supply of components to local centers, assembly of lamps at required quality, awareness campaigning, demand generation, sales, and diffusion/ uptake of the product in communities. These diverse elements were brought together in a cohesive system dynamics model to explore implementation. Three feedback loops – continuous quality improvement, demand stimulation and work fatigue – are identified and their roles in the dynamics of the project are discussed. An aggregate causal loop diagram is presented, based on which a detailed system dynamics simulation model was developed. The model is calibrated to project implementation data and used to discuss emerging dynamics. The contribution of the paper is in bringing together elements of supply & production, new product diffusion and project management dynamics, which can be also be used for understanding the roll-out dynamics of other large scale technology intervention projects.

INTRODUCTION

Around the world, several large-scale technology intervention projects are being carried out in the areas of health care, energy, water, sanitation, etc. Most of the publications about such projects are, rightly so, on the impact of such interventions on the community, and the sustainability of the intervention. However, there is a lack of literature on the dynamics of project implementation and the associated insights.

One such intervention, discussed in this paper, is the dissemination (sales) of one million solar study lamps to as many school students in rural India within limited project duration (Sawal et al., 2015). The management of a project of this scale is quite challenging due to its spread across various geographical locations. Since the project involves the sale of new products in the rural community, its uptake may be akin to a new product diffusion process. Further, the inventory operations and processes play a critical role in ensuring that the lamps reach the intended beneficiaries. Thus, a system dynamic model that effectively captures the dynamics of the implementation must include aspects of projects dynamics, new product diffusion and production-inventory dynamics.

Project management has been well-studied using system dynamics, starting with Cooper (1980). A variety of work has followed on the core project dynamics model, its extensions and applications in a variety of areas (Lyneis and Ford, 2007). However, most of the literature focuses on construction project management (Love et al., 2002; Han et al., 2013) or software project management. The basic structure of these project dynamics models include the rework cycle (Sterman, 2000), consisting of four stocks or levels: Work to be Done, Work Done, Undiscovered Rework, and Know Rework. This framework is readily amenable for projects with standard processes and work content divisions such as construction or design projects with a specific deliverables.

The diffusion of new products in markets is well studied in literature, primarily based on Bass models (Bass, 1969) and its extensions (Ho et al. , 2002; Mahajan et al., 1990; Peres et al., 2010). These models typically assume infinite supply (Peres et al., 2010), though there are recent papers that look at the effect of supply constraints and supply uncertainties on the diffusion dynamics (Ho et al., 2002; Kumar and Swaminathan, 2003; Negahban and Smith, 2016). Also, in the classical Bass model (Bass, 1969) and most of its extensions (Peres et al., 2010) the coefficient of innovation and coefficient of imitation that drives the adoptions are assumed to be exogenous constant parameters. However, the Bass family of models does provide a fundamental modeling construct to help understand diffusion dynamics.

The applications of system dynamics methodology to supply chains and production-inventory systems are aplenty, with the foundations laid by Forrester (1961) in his *Industrial Dynamics.* The basis for many of the models in literature is the classical stock management structure (Sterman 2000), used to understand the inventory dynamics of supply chains, as well as determine the best ordering policy in the face of stationary demand patterns. Other aspects of production systems include capacity utilisation and expansions, workforce inventory interaction, forecasting, management of backlogs, etc (Sterman 2000).

This paper presents the preliminary system dynamics (SD) model developed to understand and analyze the project implementation dynamics of the Million SoUL project. The SD model brings together elements of new product diffusion dynamics, production-inventory dynamics, workforce interactions, and project dynamics. The next section describes the project under study and its performance. The key reference modes are identified and the possible events in the project that might explain the dynamics are explored. A high-level causal loop model is then described, identifying three key causal loops that explain the observed dynamics. The detailed stock-flow based SD model is then presented. Simulation results show that the SD model captures the actual project dynamics accurately. Observations are drawn from the simulation results and the changing loop dominances. The paper concludes with a discussion and the way forward.

THE MILLION SoUL PROJECT AND ITS PERFORMANCE

The project discussed in this paper is the Million Solar Urja[1] Lamp (SoUL) project, planned and implemented by Indian Institute of Technology Bombay, India during 2014-2015 (Sawal et al. 2015). The goal of the project was to provide high quality, clean energy access in the form of a solar study lamp to one million school students in rural India in a rapid and cost-effective manner. The crux of the project involves localization, where in local Assembly-Distribution (A-D) centers were set up in the blocks selected for intervention[2]. The A-D centers catered to the demands in their block and 1-2 adjoining blocks, as the case may be. Further, local people were recruited from across the blocks, trained and employed at the A-D centers to assembly and distribute the lamps. The SoUL lamps were sold at Rs. 120 to school going children in their respective schools. The purchase of the lamps was optional. The distribution of lamps was carried out in multiple blocks simultaneously until the overall target of reaching one million students was completed. Care was taken to ensure that a significant percentage of the intervention blocks' student population was covered. Once the distribution was completed in a block, the A-D center was closed. Multiple local repairs centers, operated by trained locals, were established to ensure that after-sales services were provided to the student beneficiaries. The project was implemented in two phases. In Phase 1 (January 2014 to April 2015), about 735,000 lamps were distributed, and in Phase 2 (November 2015 to April 2016), 265,000 lamps were distributed. Over the course of the project, about 54 A-D centers and 350 repair and maintenance centers were in operation, providing solar study lamps across 97 blocks in the states of Odisha, Madhya Pradesh, Maharashtra and Rajasthan in India. In this paper, the distribution dynamics pertaining to Phase 1 of the project is discussed.

The week-wise distribution and the cumulative distribution of the overall project performance aggregated across all A-D centers and blocks are shown in Figure 1. The progress of the project is plotted from week 0 (when project started) until week 76 when the Phase 1 distribution was completed. At the outset the adoptions of the solar lamps by the students seems to mimic the classical S-Shaped growth (e.g. Bass model) of innovation diffusion. However, upon careful inspection of the cumulative distribution dynamics, the following points emerge:

- It is observed that from week 0 until week 8, there is no sale of lamps; and from week 8 to about week 25 the sales shows a limited linear growth.
- It is observed that from week 25 to about week 44 there seems to be an exponential growth in sales, followed by an increase in sales at an even higher rate of growth (surprisingly) from week 45-55. This is contrary to what one may expect under classical S-Shaped growth where the point of inflection occurs at halfway mark, after which the growth in sales happens at a decreasing rate.
- Next, it is seen that after week 56, the sales increases at a decreasing rate, exhibiting a classical goal-seeking behavior, finally saturating at 740112 lamps (includes the sample lamps used in marketing) at week 76.
- Also, a clear breaks in distribution are observed in week 45 and in weeks 55-56.

[1] Urja means Energy in Hindi/ Sanskrit

[2] Blocks are sub-districts, also known as *talukas* or *tehsils*. The rural intervention blocks were chosen based on percentage of households that depend on kerosene as their primary source of lighting and the backward nature of the blocks.

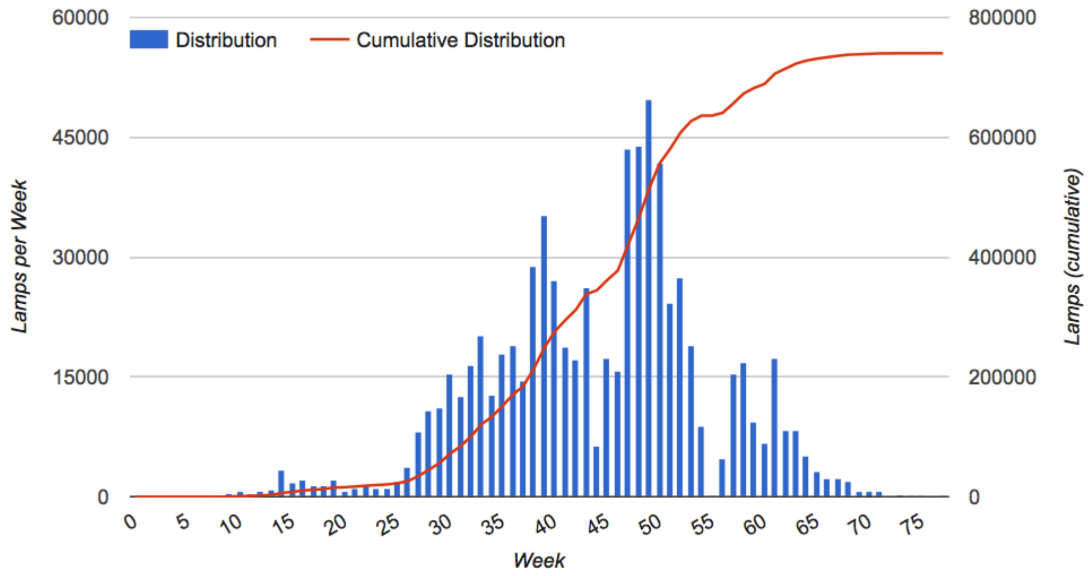


Figure 1. The actual aggregated weekly and cumulative distribution of lamps (reference modes)

These observations necessitate a closer look at the other events of project that might have influenced the dynamics.

As mentioned earlier, the project involves the local assembly of solar lamps by locally trained people. Thus, the supply of kits and the availability of manpower can be expected to influence the distribution dynamics. As seen from Figure 2, the first supply of components started in week 8, steadily increasing over the weeks with significant deliveries happening after week 36. The last shipment of components was on week 56. The first employee training happened in week 0 (the week of first training is taken as week 0 for modeling purposes), creating a workforce between weeks 18 to 35. What is not apparent from these figures is that the total supply was 747950 component kits, but the total distribution was only 740112 lamps. The difference, due to a loss of lamps as scrap, can be attributed to the quality of the assembly and distribution process. It was discovered that the initial trainings were only on the technical aspects of the lamp assembly. After observing the performance, additional quality improvement programs were carried out as part of the project to reduce the defectives, beginning in week 20. Since distribution of the lamps was primarily via schools, the school-working calendar[3] also affected the distribution pace.

Further, the original project deadline was to complete the distribution in 6 months (24 weeks). However, due to supply delays and delays in setting up new A-D centers, the project deadline was continually shifted with an eventual deadline of 64 weeks. Figure 1 demonstrates that this deadline was also not met, perhaps due to a lack of motivation to complete the project, trained local people moving on to other opportunities, or a slower pace of work etc. This is perhaps akin to the popular "90% syndrome" in project management dynamics literature (Ford and Sterman 1999).

[3] In India, the school-working calendar varies across states, but typically, the academic session starts by July; with short break (a week or less) in mid-October, end of December, and summer breaks in the months of April-June.

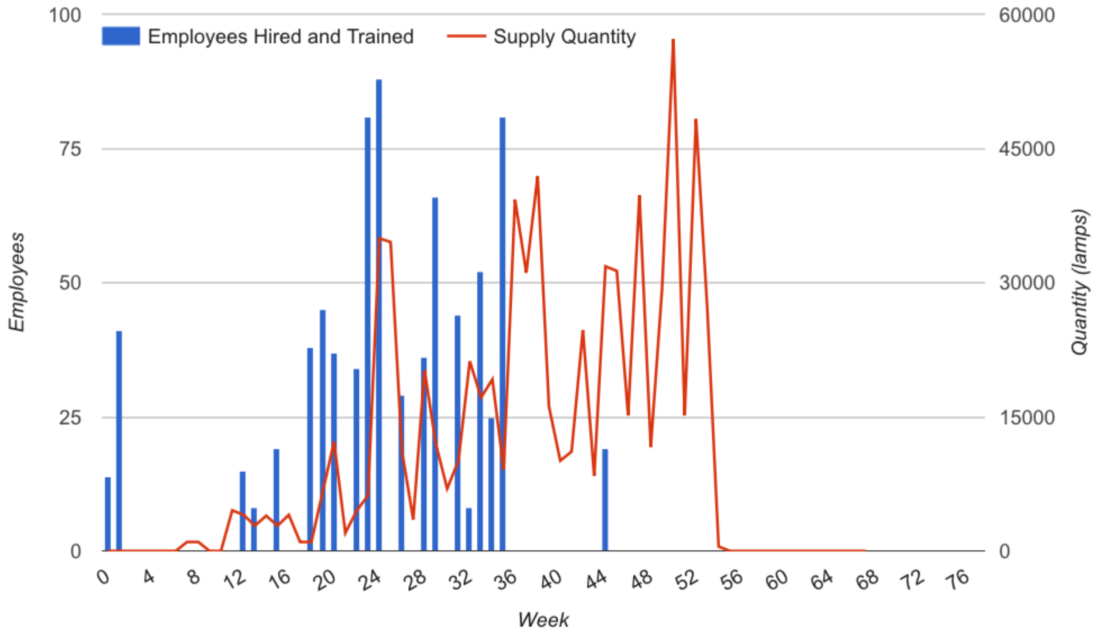


Figure 2. Aggregated employees hiring and supply of components, over weeks

MODEL DEVELOPMENT

In this paper, a system dynamics model is developed to help explain the distribution dynamics (see Figure 1) as observed in the project. In this model, the supply of components to A-D centers and the hiring and training of local employees are considered as exogenous variables. This is to help uncover the other project dynamics that influences the distribution. The causal loop diagram with the key variables along with the essential stocks and flows are shown in Figure 3. An important distinction is made between the student beneficiaries (adopters of the lamp) and the lamp itself. The student beneficiaries are captured as stocks of *Potential Adopters* and *Adopters*. The *Adoption Rate* is governed by dynamics similar to the Bass Diffusion model but constrained by the *school working calendar* as will be discussed further. The *Supplying* of lamps components increases the stock of *Lamp Kits at A-D centers*. Assuming sufficient demand and capacity, these lamp kits are distributed, increasing the *Lamps Distributed*. As the lamps are distributed, the *actual project progress* is compared with the *planned project progress*. As the gap in progress increases, project managers perceive *pressure to complete the project*. The model captures that they respond with *efforts to increase demand* by increasing *advertising efforts*. As more *Adopters* adopt the technology it increases *demand*, which when satisfied, increases the *Lamps Distributed*, improving the project progress and reducing the shortfall. However, in the long run, working under the pressure of deadlines increases *fatigue* among the employees that decreases their *productivity* and the *available capacity*, leading to lesser lamps begin distributed, and thus a smaller increase in Lamps Distributed. This eventually reduces the *pressure to complete the project*, reducing *fatigue*.

The *desired assembly distribution rate* is constrained by the *demand* or the *lamp kits in A-D centers*, with the eventual assembly and *distributions* constrained additionally by the *available capacity*. Also, similar to any production process operating at given

Process Quality, *Scraps* are also generated at the A-D centers that decrease the *perceived quality levels*. As the perceived levels fall below the *desired quality level*, *Quality Improvement Programs* are initiated which increases the *Process Quality*, resulting in reduced *defects and scrap*.

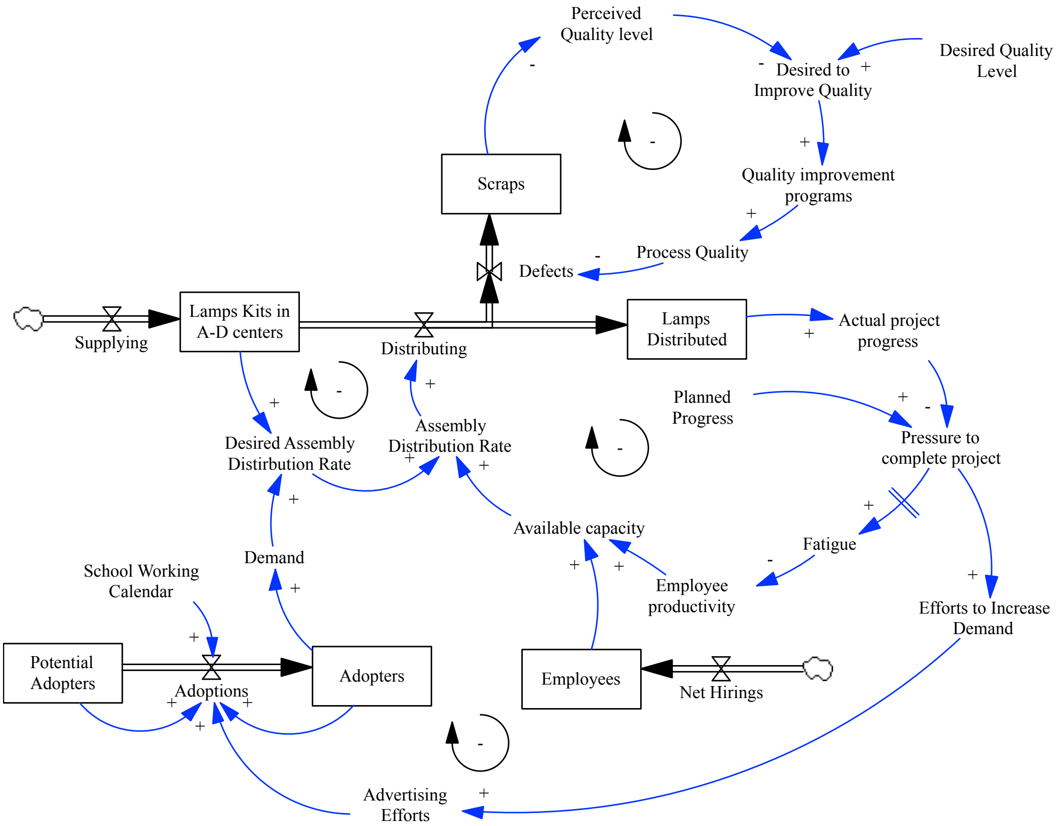


Figure 3. Basic causal loop diagram

THE STOCK-FLOW SD SIMULATION MODEL

A complete Stock-Flow based system dynamics simulation model, of the above CLD is developed (see Figure 4). It is described in this section. The underlying equations are presented in the Appendix.

An additional loop for the identification, dispatch and replacement of defective components by the suppliers is added (see top left of Figure 4). The defective components, identified by inspection and testing at the A-D centers are moved into a stock of *defectives at A-D centers*. These defectives are then dispatched to the suppliers who replace them with good components after some delay.

The adopters or beneficiaries are divided into two stocks of *Adopters* and *Active Adopters* (see bottom left of Figure 4). The *Adopters* are those who have adopted the technology and are ready to buy the lamp, while *Active Adopters* are those who have actually purchased the solar lamp. The *Adoptions due to Advertising* and the *Adoptions due to Word of Mouth* that drives *Adoption Rate* is similar to the classical Bass Diffusion model. However, in this model, the *Adoption Rate* is also influenced by the *School Working Calendar, as follows:*

```
Adoption Rate =
    (Adoptions due to Advertising + Adoptions due to Word of Mouth)* School
Working Calendar
```

In the weeks the schools are in full session, *School Working Calendar* takes value 1 to indicate a regular *adoption rate*. In the week with summer breaks, examinations, and other holidays, the School Working Calendar takes a value < 1 (0.2 in our case) to indicate lower rates of adoption.

The human resource (employees) is split across three stocks, *Idle New Hires, Trainees,* and *Experienced Employees,* each with their own productivity levels (see bottom right of Figure 4). The *Idle New Hires* refers to those employees who are hired but are idle due to unavailability of lamp components at the A&D centers to work on.

There are four table functions in this model: *Utilisation*, *Quality Improvement Efforts*, *Advertising Efforts* and *Motivation*, as shown in Figures 5(a) – 5(d). The *Utilisation* appears in the capacity management loop that determines the weekly *assembly distribution rate*, as follows:

```
Assembly Distribution Rate = Available Capacity*Utilisation

Utilisation=f(Schedule Pressure)=f(Desired AssemblyDistributionRate/
Available Capacity)
```

The *Utilisation* table function is shown in Figure 5(a). The normal utilisation is taken as 1.0. When the *Schedule Pressure* is less than 1.0, the *assembly distribution rate* equals the desired rate. As the *Schedule Pressure* increases beyond 1, the Utilisation also increases and saturates at 1.25. This indicates the possible speeding up of activities and overtime the employees may work to meet increased demand.

Next, the *Quality Improvement Effort*, shown in Figure 5(b), appears in the quality improvement loop, and helps determine the overall rate at which the *Process Quality* level changes, as follows:

```
Process Quality = INTEG(Change in Process Quality)

Change in Process Quality =(Desired Quality Level - Process Quality) *
Quality Improvement Effort

Quality Improvement Effort=f(Perceived Quality Ratio)

Perceived Quality Ratio = SMOOTH(Actual Quality Level/Desired Quality Level,
Smoothing Delay)

Actual Quality Level  = Cumulative Distribution/ (Cumulative Distribution +
Cumulative Scraps)
```

As seen from Figure 5(b), when the *Actual Quality* is equal to or more than the *Desired Quality*, then no further quality improvement efforts (=0.0) are needed. When the *Perceived Quality Ratio* is close to 1, the required quality improvements efforts are low (<=0.4) . And when the *Perceived Quality Ratio* is close to 0, then maximum efforts to improve quality is needed (indicated by 1.0).

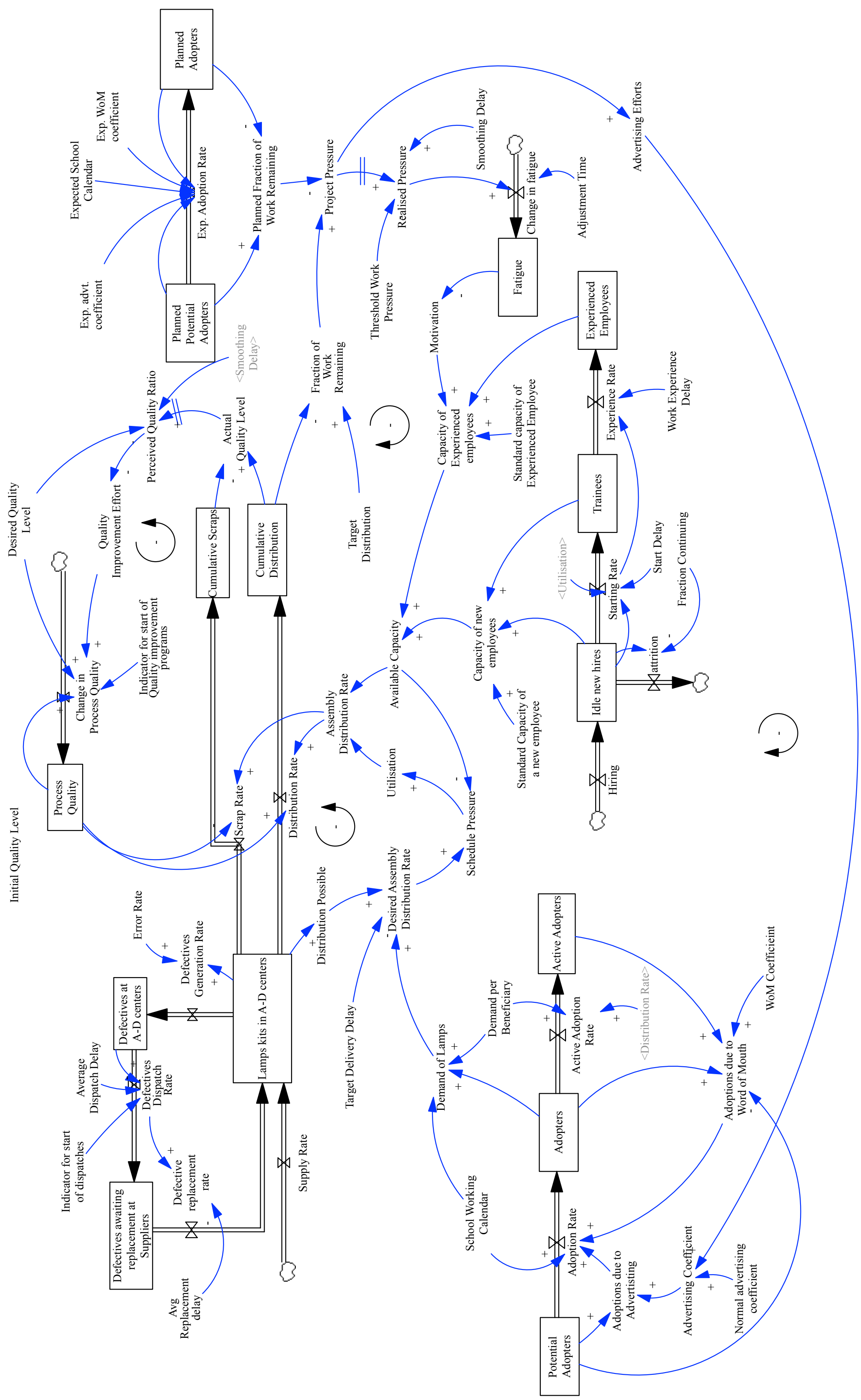


Figure 4. Detailed Stock Flow Diagram

Next, the *Advertising Efforts*, shown in Figure 5(c), appears in the demand stimulation loop, and helps determine the overall *Adoptions due to Advertising*, as follows:

```
Adoptions due to Advertising = Potential Adopters * Advertising Coefficient

Advertising Coefficient= Normal advertising coefficient*Advertising Efforts

Advertising Efforts = f(Project Pressure)

Project Pressure = (Fraction of Work Remaining-Planned Fraction of Work Remaining)/Planned Fraction of Work Remaining
```

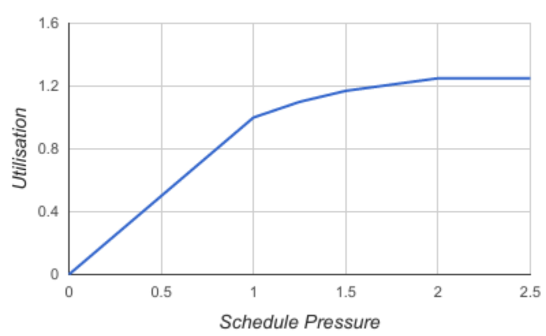
As seen from Figure 5(c), when the project pressure is less than 0.5, the *advertising efforts* remain at the normal rate of 1. However, as the pressure increases to one, the *advertising efforts* increases, reaching a maximum value of 4.0, resulting in a four-fold increase in *advertising coefficient* and the *Adoptions due to Advertising*. It is noted that the *Planned Fraction of Work Remaining* is an indicative of the planned project progress, and is computed using a classical Bass Diffusion model (see top right of Figure 4).

Finally, the *motivation* appears in the fatigue and capacity loop, as follows:

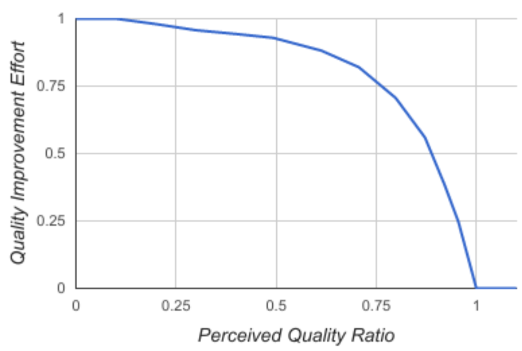
```
Capacity of Experienced employees = Motivation*Standard capacity of Experienced Employee*Experienced Employees

Motivation = f(Fatigue)
```

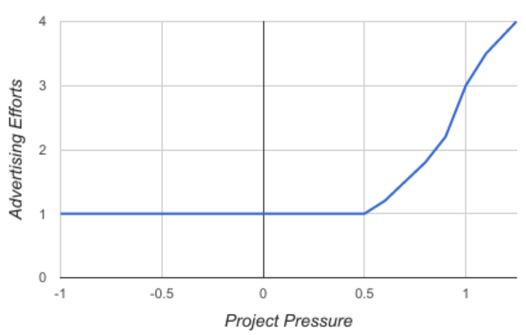
The *Fatigue* is modeled as a stock, which builds-up slowly over time depending on the project pressure. As seen from Figure 5(d), when *fatigue* crosses 1, the *motivation* rapidly decreases and saturates at 10%.



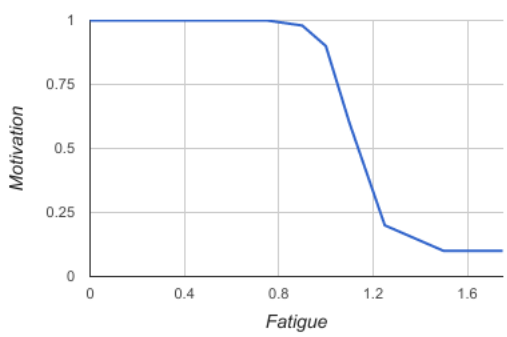
(a) Utilisation Table Function



(b) Quality Improvement Table Function



(c) Advertising Efforts Table Function



(d) Motivation Table Function

Figure 5. Table functions used in the model

SIMULATION RESULTS AND ANALYSIS

Model verification

The above simulation model was implemented using Vensim® PLE. Before calibrating of the specific scenario on hand, the model was verified. First, the dimensional consistency was verified and the model was tested for robustness at extreme conditions (Barlas, 1996). When any one of the three, *Supply Rate* or the *Hiring* or *Adopters* are 0, then the *Distribution rate* is 0, irrespective of the values of the other two variables. Other combined parameter settings were also verified to ensure the model behavior is as expected. For instance, suppose that the *initial quality level* is 0, but the *supply rate* has a pulse input of 1000 as time 40, then the *quality improvement efforts* does not begin until the distribution takes place, and the system performance (*cumulative scraps* and *cumulative distribution*) are observed.

Model Calibration

The *school working calendar* is a proportionality constant with value 1 on school working weeks, and value 0.2 on school non-working weeks. The parameter values were set based on the actual project performance data (both quantitative and qualitative), is shown in Table 1. Further, the *Supply Rate* and *Hiring* are exactly as in Figure 2, captured using PULSE function in Vensim. The project was rolled out such that the total target, beginning at 1 million was revised downwards (a decision based on fund availability). This is captured in the *Target Distribution* parameter (as 1000000-STEP(100000,15)-STEP(100000,35)-STEP(55000,40)). It is noted that in week 15 the *target distribution* was reduced to 900000, and the next revision was only in week 35. However, by 35 weeks almost all the required manpower was already hired (see Figure 2) and the required number of A-D centers established. Hence the initial value of *Potential Adopters* was set at 900000.

Table 1: Parameter Settings

Parameter	Value
Error Rate	0.025/week
Average Dispatch Delay	1 week
Average Replacement Delay	3 week
Fraction continuing	0.8/week
Work Experience Delay	2 week
Demand per Beneficiary	1 Lamp/ Beneficiary
Standard Capacity of New Employees	10 Lamps/ Week/ Employee
Standard Capacity of Experienced Employees	60 Lamps/ Week/ Employee
Target Delivery Delay	1 Week
Smoothing Delay	4 Week

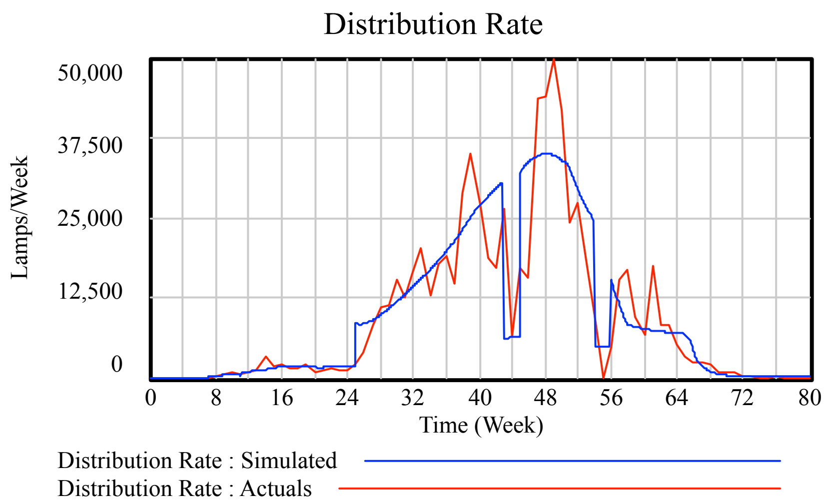
The diffusion parameters of *WoM Coefficient* and *Normal Advertising Coefficient* were determined empirically by calibrating the model against the actual project performance (Figure 1). The *WoM Coefficient* at 0.12 and the *Normal Advertising Coefficient* at 0.005 was found to give the closest fit to the actual data.

Simulation Results

The model is simulated with a time step of 0.125 weeks. Figures 6 show the plots of *Distribution Rate* and the *Cumulative Distribution*, comparing the simulation results and the actual data. As seen from the figure, the model is able to quite accurately replicate the project dynamics.

The dynamic behavior of the other variables was explored to help understand the shifts in loop dominance. Towards that, three plots are presented in Figure 7. The top-most plot in Figure 7 presents the quality improvement effects. It clearly shows that the scraps were generated at an increasing rate from week 8. In week 20, the project initiated quality improvement programs, which, after some delay increased the *process quality* to the desired levels by week 30. This significantly reduced the rate of growth of scraps from week 22 onwards.

Next, the middle plot in Figure 7 shows the *Assembly Distribution Rate*, the *Distribution Possible* and the *Demand of Lamps.* Only at the initial weeks (week 8 to 15) and the closing weeks (week 65 onwards), the Distribution Rate is constrained by the material available (captured by *Distribution Possible)*. During weeks 15 to 55 the distribution rate is determined only by the *demand of lamps* from the field. However, in weeks 46 to 49, the *Assembly Distribution Rate* was lower than the demand. This was due to the available capacity utilisation where in the employees were unable to keep pace with the demand. Also, from week 55-65, the *Assembly Distribution Rate* is again determined by the available capacity of the employees. To further understand the sudden increase in Demand rate (weeks 45 to 55) and the sudden decrease in assembly distribution rate are shown in the bottom-most plot in Figure 7. It depicts the effect of project pressure on the project dynamics. Until week 23 the *project pressure* was low, considering the school working calendar and the fact that the manpower (employees) were still being recruited and trained. From weeks 24-35 the *project pressure* grows indicating the increasing shortfall between the planned project progress and the actual project progress. After week 35, when *project pressure* cross 0.5, the *Advertising coefficient* also increases, peaking at 0.2 in week 46. This increase in *Advertising coefficient* causes an increase in *demand of lamps*, during the weeks 45-55. Once the *project pressure* crosses the *threshold pressure* of 1, it starts to add to the *fatigue*. As *fatigue* grows beyond 1 in week 54, the *capacity of experience employees* begins to fall, reaching a new low after week 58. This reduction in the *capacity of experience employees* causes the reduction in the *assembly distribution rate* after week 55.



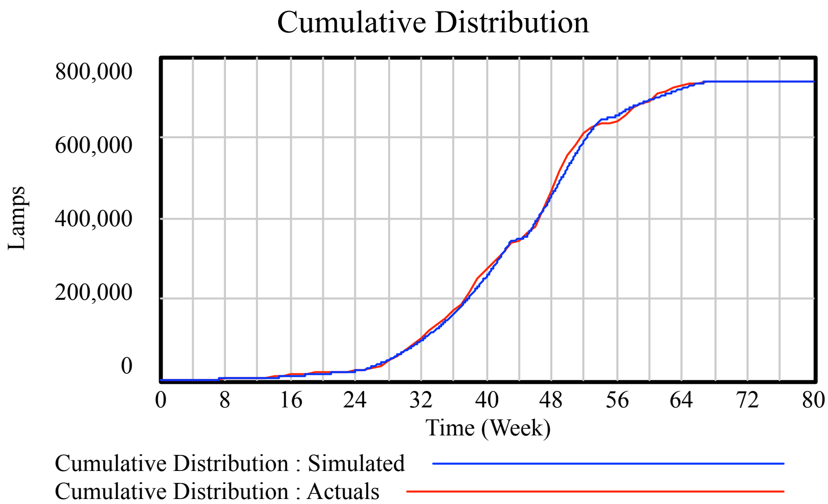


Figure 6. Simulated results vs. Actual data for the reference modes

Figure 7. The dynamic behavior of key model variables

DISCUSSION

This paper presents a preliminary model towards understanding the dynamics of the Million Solar Urja Lamp project. A brief background of the project is given and the actual project performance discussed. The key reference modes are identified and the possible events in the project that might explain the dynamics are explored. A high-level causal loop diagram was developed to identify three key causal loops that explain the observed dynamics: the quality improvement loop, demand stimulation loop and the work fatigue loop. A detailed stock-flow based system dynamics model was then developed, tested, calibrated and simulated. Simulations show that the model explains the actual project dynamics. The dynamic behaviors of the other variables are also explored to help understand the shifts in loop dominance within the model.

The model provides a variety of insights from a project management perspective. The school-working calendar plays a critical role in project timing that needs to be accounted for in project planning. This speaks to a larger need to consider constraints on adoption for project management. In this case, because implementation took place in a school setting, adoption was limited to when children were in school despite advertising efforts. There may be similar place-based limitations in other technology interventions that should be considered in project management. The model also highlights the importance of continuous quality control, which is particularly critical when assembly is established locally. Understanding the flow of scraps and its impact on perceived quality allows project managers to trigger quality control, in this case through providing quality control programs to reduce the number of defective lamps.

Disaggregating beneficiaries from the technology intervention allowed us to unpack their dynamics and explore how they interacted with employee capacity. The model makes it explicit that adopters drive demand for the technology that affects the desired assembly distribution rate creating schedule pressure. However, even if there is sufficient employee capacity to assemble and distribute technology they are constrained by the availability of supplies, potentially slowing cumulative distribution (project progress). We demonstrated how this has interesting implications for employee fatigue, where project pressure created by a low level of cumulative distribution builds project pressure leading to fatigue. Employee fatigue can lower motivation, limiting the capacity of employees. The takeaway is that project managers should consider and manage employee fatigue, especially in light of distribution slowdowns or supply shortages. We found that project managers also reacted to pressure to complete the project by increasing advertising to spur demand for the technology. The model demonstrates that this will only be effective if there is sufficient employee capacity and supply to meet increased demand. These factors may play a role in other efforts to provide technology interventions with a locally sourced workforce, assembly and distribution.

The model was presented and discussed with Million SoUL project managers. The managers felt that the model helped make it quite clear to them that school working calendar plays a critical role in the project roll-out and needs to be factored in their project planning. The managers also mentioned that the slow build of fatigue due to protracted project activities and its influence on the dynamics during the last few weeks was a new insight. Also, since a large part of the project management team efforts was actually focused on ensuring the supply of components to the A-D centers, the replacement of defectives, and the assembly of lamps, the view presented in that model that demand for lamps as the driving force, was a new learning to them. The managers also pointed out that the *Supply Rate* and *Hiring* were key project management decisions, with *Supply Rate* constrained by the suppliers' capacities and *Hiring* reflecting the decision to expand to new blocks. The model could be used as a tool to aid in these decisions in the future A few what-if scenarios are being designed to help deepen the understanding of the project dynamics and inform future implementation. Further, it was suggested to include the cost or expenditure dynamics as part of the model. Work is ongoing to include these dynamics as part of future system dynamics project models.

The contributions of the paper can be viewed from two aspects, over and above the learning of modelers and the project management team. One, we have shared an interesting case study, walking though the background, reference models, model elicitation, casual loop modeling, detailed SD modeling and analysis, which one may find useful to replicate in other settings or provide insights for future project implementation. Two, in the model the technology intervention (solar lamp) is considered distinct from the beneficiaries of the solar lamp although they are inter-connected; the project progress is explicitly captured along with its influence on both the demand (Adopters) as well as supply (assembly and distribution). This construct may be useful in modeling other large-scale technology interventions.

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APPENDIX

The complete model documentation, as obtained from Vensim is presented here.

(01) Active Adopters= INTEG (
Active Adoption Rate,
0)
Units: Beneficiary

(02) Active Adoption Rate=
Distribution Rate/Demand per Beneficiary
Units: Beneficiary/Week

(03) Actual Quality Level=
IF THEN ELSE(Cumulative Distribution+Cumulative Scraps=0,1,Cumulative Distribution /(Cumulative Distribution+Cumulative Scraps))
Units: Dmnl

(04) Adjustment Time=
1
Units: Week

(05) Adopters= INTEG (
Adoption Rate-Active Adoption Rate,
0)
Units: Beneficiary

(06) Adoption Rate=
(Adoptions due to Advertisting + Adoptions due to Word of Mouth)*School Working Calendar
Units: Beneficiary/Week

(07) Adoptions due to Advertisting=
Potential Adopters*Advertising Coefficient
Units: Beneficiary/Week

(08) Adoptions due to Word of Mouth=
WoM Coefficieint*(Adopters+Active Adopters)*Potential Adopters/(Adopters+ Active Adopters+Potential Adopters)
Units: Beneficiary/Week

(09) Advertising Coefficient=
Normal advertising coefficient*Advertising Efforts
Units: 1/Week

(10) Advertising Efforts = WITH LOOKUP (
Project Pressure,
([(-1,0)-(1.5,4)],(-1,1),(0,1),(0.25,1),(0.5,1),(0.6,1.2),(0.7,1.5),(0.8 ,1.8),(0.9,2.2),(1,3),(1.1,3.5),(1.25,4),(1.5,4)))
Units: Dmnl

(11) Assembly Distribution Rate=
Available Capacity*Utilisation
Units: Lamps/Week

(12) attrition=
Idle new hires*(1-Fraction Continuing)
Units: Employee/Week

(13) Available Capacity=
Capacity of Experienced employees+Capacity of new employees
Units: Lamps/Week

(14) Average Dispatch Delay=
1
Units: Week

(15) Avg Replacement delay=
3
Units: Week

(16) Capacity of Experienced employees=
Motivation*Standard capacity of Experienced Employee*Experienced Employees
Units: Lamps/Week

(17) Capacity of new employees=
(Trainees+Idle new hires)*Standard Capacity of a new employee
Units: Lamps/Week

(18) Change in fatigue=
Realised Pressure/Adjustment Time
Units: 1/Week

(19) Change in Process Quality=
Indicator for start of Quality improvement programs*(Desired Quality Level
-Process Quality)*Quality Improvement Effort
Units: 1/Week

(20) Cumulative Distribution= INTEG (
Distribution Rate,
0)
Units: Lamps

(21) Cumulative Scraps= INTEG (
Scrap Rate,
0)
Units: Lamps

(22) Defective replacement rate=
DELAY N(Defectives Dispatch Rate , Avg Replacement delay , 0 , 3)
Units: Lamps/Week

(23) "Defectives at A-D centers"= INTEG (
Defectives Generation Rate-Defectives Dispatch Rate,
0)
Units: Lamps

(24) Defectives awaiting replacement at Suppliers= INTEG (
Defectives Dispatch Rate-Defective replacement rate,
0)
Units: Lamps

(25) Defectives Dispatch Rate=
Indicator for start of dispatches*"Defectives at A-D centers"/Average Dispatch Delay
Units: Lamps/Week

(26) Defectives Generation Rate=

Error Rate*"Lamps kits in A-D centers"
Units: Lamps/Week

(27) Demand of Lamps=
Adopters*Demand per Beneficiary*School Working Calendar
Units: Lamps

(28) Demand per Beneficiary=
1
Units: Lamps/ Beneficiary

(29) Desired Assembly Distribution Rate=
MIN(Distribution Possible,Demand of Lamps)/Target Delivery Delay
Units: Lamps/Week

(30) Desired Quality Level=
0.995
Units: Dmnl

(31) Distribution Possible=
"Lamps kits in A-D centers"
Units: Lamps

(32) Distribution Rate=
Assembly Distribution Rate*Process Quality
Units: Lamps/Week

(33) Error Rate=
0.025
Units: 1/Week

(34) "Exp. Adoption Rate"=
("Exp. advt. coefficient"*Planned Potential Adopters + ("Exp. WoM coefficient" *(Planned Adopters)*Planned Potential Adopters/(Planned Adopters+Planned Potential Adopters
)))*Expected School Calendar
Units: Beneficiary/Week

(35) "Exp. advt. coefficient"=
0.01
Units: 1/Week

(36) "Exp. WoM coefficient"=
0.12
Units: 1/Week

(37) Expected School Calendar=
0.3*PULSE(0 , 10) + 0.3*PULSE(10 , 4) +0.3*PULSE(14 , 9) + 1*PULSE(23 , 20)+ 1*PULSE(43 , 2)+ 1*PULSE(45 , 9)+ 1*PULSE(54 , 2)
+ 1*PULSE(56 , 13) +0.25*PULSE(69 , 12)+1*PULSE(81,32)
Units: Dmnl

(38) Experience Rate=
DELAY N(Starting Rate , Work Experience Delay , 0 , 3)
Units: Employee/Week

(39) Experienced Employees= INTEG (
Experience Rate,
0)

Units: Employee

(40) Fatigue= INTEG (
Change in fatigue,
0)
Units: Dmnl

(41) FINAL TIME = 80
Units: Week
The final time for the simulation.

(42) Fraction Continuing=
0.8
Units: 1/Week

(43) Fraction of Work Remaining=
(Target Distribution-Cumulative Distribution)/Target Distribution
Units: Dmnl

(44) Hiring=
14*PULSE(0,1)+41*PULSE(1,1)+15*PULSE(12,1)+8*PULSE(13,1)+19*PULSE(15,1)+38
*PULSE(18,1)+45*PULSE(19,1)+37*PULSE(20,1)+34
*PULSE(22,1)+81*PULSE(23,1)+88*PULSE(24,1)+29*PULSE(26,1)+36*PULSE(28,1)+
66*PULSE(29,1)+44*PULSE(31,1)+8*PULSE(32,1)+52
*
PULSE(33,1)+25*PULSE(34,1)+81*PULSE(35,1)+19*PULSE(44,1)
Units: Employee/Week
50*PULSE(1,1)+80*PULSE(10,1)+100*PULSE(20,1)

(45) Idle new hires= INTEG (
Hiring-attrition-Starting Rate,
1)
Units: Employee

(46) Indicator for start of dispatches=
STEP(1,16)
Units: Dmnl

(47) Indicator for start of Quality improvement programs=
STEP(1 , 21)
Units: 1/Week

(48) Initial Quality Level=
0.825
Units: Dmnl [0.5,1,0.025]

(49) INITIAL TIME = 0
Units: Week
The initial time for the simulation.

(50) "Lamps kits in A-D centers"= INTEG (
Defective replacement rate+Supply Rate-Distribution Rate-Defectives Generation Rate
-Scrap Rate,
0)
Units: Lamps

(51) Motivation = WITH LOOKUP (
Fatigue,
([(0,0)-(1.8,1)],(0,1),(0.25,1),(0.5,1),(0.75,1),(0.9,0.98),(1,0.9),(1.1

,0.6),(1.25,0.2),(1.5,0.1),(1.75,0.1)))
Units: Dmnl

(52) Normal advertising coefficient=
0.005
Units: 1/Week

(53) Perceived Quality Ratio=
SMOOTH(Actual Quality Level/Desired Quality Level,Smoothing Delay)
Units: Dmnl

(54) Planned Adopters= INTEG (
"Exp. Adoption Rate",
0)
Units: Beneficiary

(55) Planned Fraction of Work Remaining=
Planned Potential Adopters/(Planned Adopters+Planned Potential Adopters)
Units: Dmnl

(56) Planned Potential Adopters= INTEG (
-"Exp. Adoption Rate",
900000)
Units: Beneficiary

(57) Potential Adopters= INTEG (
-Adoption Rate,
900000)
Units: Beneficiary

(58) Process Quality= INTEG (
Change in Process Quality,
Initial Quality Level)
Units: Dmnl

(59) Project Pressure=
MAX(Fraction of Work Remaining-Planned Fraction of Work Remaining,0)/Planned Fraction of Work Remaining
Units: Dmnl

(60) Quality Improvement Effort = WITH LOOKUP (
Perceived Quality Ratio,
([(0,0)-(1.1,1.1)],(0,1),(0.1,1),(0.2,0.98),(0.299389,0.957346),(0.401222
,0.943128),(0.492872,0.92891),(0.613035,0.881517),(0.706721,0.819905),(0.798371
,0.706161),(0.87169,0.559242),(0.92057,0.383886),(0.955193,0.246445),(1,0)
,(1.1,0)))
Units: Dmnl

(61) Realised Pressure=
SMOOTH(MAX(Project Pressure-Threshold Work Pressure,0),Smoothing Delay)
Units: Dmnl

(62) SAVEPER =
TIME STEP
Units: Week [0,?]
The frequency with which output is stored.

(63) Schedule Pressure=
(Desired Assembly Distribution Rate/MAX(1,Available Capacity))

Units: Dmnl

(64) School Working Calendar=
0.2*PULSE(0 , 10) + 0.2*PULSE(10 , 4) +0.2*PULSE(14 , 11) + 1*PULSE
(25 , 18)+ 0.2*PULSE(43 , 2)+ 1*PULSE(45 , 9)+ 0.2*PULSE(54 , 2)
+ 1*PULSE(56 , 13) +0.2*PULSE(69 , 12)+1*PULSE(81,32)
Units: Dmnl

(65) Scrap Rate=
(1-Process Quality)*Assembly Distribution Rate
Units: Lamps/Week

(66) Smoothing Delay=
4
Units: Week

(67) Standard Capacity of a new employee=
10
Units: Lamps/Week/Employee

(68) Standard capacity of Experienced Employee=
60
Units: Lamps/(Week*Employee)

(69) Start Delay=
1
Units: Week

(70) Starting Rate=
Idle new hires*Utilisation/Start Delay
Units: Employee/Week

(71) Supply Rate=

1010*PULSE(7,1)+1010*PULSE(8,1)+4545*PULSE(11,1)+4040*PULSE(12,1)+2800*PULSE
(13,1)+3900*PULSE(14,1)+2800*PULSE(15,1)+4040*PULSE(16,1)+1010*PULSE(17,1)
+1010*PULSE(18,1)+6600*PULSE(19,1)+12221*PULSE(20,1)+2020*PULSE(21,1)+4500
*PULSE(22,1)+6262*PULSE(23,1)+34946*PULSE(24,1)+34542*PULSE(25,1)+11211*PULSE
(26,1)+3535*PULSE(27,1)+20200*PULSE(28,1)+12120*PULSE(29,1)+6969*PULSE(30,
1)+10100*PULSE(31,1)+21210*PULSE(32,1)+17170*PULSE(33,1)+19190*PULSE(34,1)
+9090*PULSE(35,1)+39289*PULSE(36,1)+31100*PULSE(37,1)+41915*PULSE(38,1)+16160
*PULSE(39,1)+10100*PULSE(40,1)+11110*PULSE(41,1)+24650*PULSE(42,1)+8383*PULSE
(43,1)+31815*PULSE(44,1)+31310*PULSE(45,1)+15150*PULSE(46,1)+38770*PULSE(47
,1)+11615*PULSE(48,1)+29290*PULSE(49,1)+57241*PULSE(50,1)+15150*PULSE(51,1
)+48278*PULSE(52,1)+27068*PULSE(53,1)+505*PULSE(54,1)
Units: Lamps/Week

(72) Target Delivery Delay=
1
Units: Week

(73) Target Distribution=
1e+06-STEP(100000,15)-STEP(100000,35)-STEP(55000,40)
Units: Lamps

(74) Threshold Work Pressure=
1
Units: Dmnl

(75) TIME STEP = 0.125
Units: Week [0,?]
The time step for the simulation.

(76) Trainees= INTEG (
Starting Rate-Experience Rate,
0)
Units: Employee

(77) Utilisation = WITH LOOKUP (
Schedule Pressure,
([(0,0)-(2.5,1.25)],(0,0),(0.25,0.25),(0.5,0.5),(0.75,0.75),(1,1),(1.25,
1.1),(1.5,1.17),(1.75,1.21),(2,1.25),(2.25,1.25),(2.5,1.25)))
Units: Dmnl
([(0,0)-(2.5,2)],(0,0),(0.249491,0.32),(0.5,0.64),(0.75,0.86),(1,
1),(1.25,1.1),(1.5,1.17),(1.75,1.21),(2,1.25),(2.25,1.25),(2.5,1.
25))

(78) WoM Coefficieint=
0.12
Units: 1/Week

(79) Work Experience Delay=
2
Units: Week