Machine Strategy Evaluation Using Group Model Building in System Dynamics

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Abstract

Modeling projects, in order to build richer understanding of the dynamics of real-world phenomena in manufacturing systems, benefit from utilizing System dynamics group model building. This paper describes a project utilizing such method in order to identify the interrelated dynamics of aging machinery equipment, competence development, and level of automation for accurate manufacturing systems development. These central aspects were identified by the project group during modeling and were considered vital in order to approach the proper Machine Strategy for the system of interest. Aspects of attention in the study also considered participants' learning of the system of interest, participants' perception upon model results, and the comparison between utilizing group model building and the traditional modeler-client approach. It is shown that System dynamics group model building has potential use in manufacturing, and indeed that more efforts are needed for successful use in projects. For that reason the need of a framework for supporting system dynamics projects in manufacturing is identified.

Keywords: system dynamics, group model building, manufacturing systems development

Introduction

Modeling is a matter of course in order to evaluate and assure powerful improvements of manufacturing systems. However in practice, improvement efforts are often limited by our abilities to think; generally assuming cause and effect to be closely related in time and space (Repenning and Sterman, 2001). It limits our ability to correctly understand the feedback among system components in complex systems. This research acknowledges that in order to achieve more efficient production it requires simulation analysis to identify improvements with lasting results. The case study presented in this paper explores system dynamics, using group model building, as a method to evaluate and assure operative system improvements. The study focused on the level of industrial plant equipment strategy (Machine Strategy) at a medium sized manufacturer in Sweden.

System dynamics (Forrester, 1961, 1968; Sterman, 2000; Morecroft, 2007) can be applied to identify the dynamics of problems. It may facilitate understanding the internal dynamics of a problem boundary, and in due time provide basis for a common view among problem stakeholders for how to solve it. Moreover, simulation provides experimenting on future policies for improvement and can verify robustness of solutions for implementation. Group model building (Vennix, 1996) is a method for carrying out modeling projects and is also termed “modeling for learning” by (Morecroft and Sterman, 1994). Group model building utilizes group interventions as a mean to assure the desired effects from a system dynamics project, in which one main aspect is to bring group member opinions about problem phenomena together. Primary objective of group model building is to involve a group of people “in building a system dynamics model of a problem in order to see to what extent this process might be helpful to increase problem understanding and to devise courses of action to which team members will feel committed” (Vennix, 1996). The opportunities from applying group model building motivate using it for facilitating manufacturing systems development.

This paper mainly focus on describing a case study that utilized group model building in order to explore how to deal with aging machinery in a manufacturing context. However, in the discussion this paper also examines some three questions of interest in order to enrich learning about the participants’ experience from the modeling case and how the results were received. The evaluation of group members experiences regard if they consider themselves have attained learning about the modeled system and how they view upon model results. Yet, a comparison between this study and a previous industrial modeling case not using group model building by Linnéusson *et al*., (2008) is presented, in order to contrast differences of use for facilitating manufacturing systems development.

Modeling

In system dynamics modeling the structure of a system is mapped. Mapping includes parameters in the system of interest for a certain problem situation. Further it includes how the state in these parameters is created from causes and effects. It results in a structure of feedback representing the internal dynamics of the modeled system. The model described in this paper does not consider any external factors such as financial cycles or possible impact from major breakthroughs in manufacturing technologies.

Model purpose

Purpose with modeling was to increase understanding of industrial plant equipment development dynamics at a certain production site in relation to customer orders, simply exploring a rewarding machine strategy. And, as part of these dynamics, analyze how the present problem situation of aging machines may improve.

Project outline

The guidelines in Vennix (1996) supported designing the outline of this project.

1. Designing a modeling project description. This was initially generally described without pointing out a specific problem on beforehand.
2. Identifying project and project group. The client found it an urgent problem, thus a project worth carrying through. Suitability for system dynamics was identified using

sector mapping (Richmond, 1994) which showed feedback in the model. A seven people group, selected by the client, was used that had decision making responsibility.

3. A preliminary model (Vennix, 1996) was used as basis for facilitating the modeling sessions. Using a preliminary model was due to that it was the first group model building project conducted by the researcher. Another aspect was that all roles in a modeling team (Vennix, 1996) were held by the researcher. In this way the level of modeling in real time was kept on a minimum providing time for discussion upon problem phenomena and model development.
4. Interviews were conducted, individually before starting any group sessions in order to involve and introduce group members on the subject. It provided input data in order to compile preliminary modeling in order to identify stocks and flows without complete feedback loops, termed "*operational thinking*" (Richmond, 1994).
5. The first modeling session drafted and revised the preliminary model.
6. Between session one and two a workbook was developed by the researcher and filled in individually by the group members.
7. The collected data from the workbooks was implemented into the model, adding structure and closing feedback loops.
8. The second modeling session drafted the results from the workbooks. It also implemented workbook material into the model which was drafted and revised.
9. Between sessions two and three quantification started (defining algebraic relations and closing feedback loops in the model).
10. Third modeling session drafted model results and the first simulation of problem dynamics was carried out, bringing further modeling and discussions.
11. Extra modeling session that drafted model results, as a consequence of interest (this was not included in the original project description).
12. A present state was designed (based on input data from previous group sessions) and experiments on future policy changes were carried out in order to identify consequences of change.
13. Results were presented in combination with an evaluation of how the group members thought the project had evolved.
14. Evaluation Questionnaire filled in by the project members.
15. Project report summarized the complete modeling effort and was handed over to the organization.

Model description

The machine strategy was divided into four parts considered to interrelate according to the simplification of the complete model shown in figure 1 below. In appendix A-D the detail models are also shown. Therefore, in order to better understand following model descriptions the reader may look into appendix A-D. However, in figure 1 the internally created dynamics are illustrated; all parameters depend on each other besides a few defined constants.

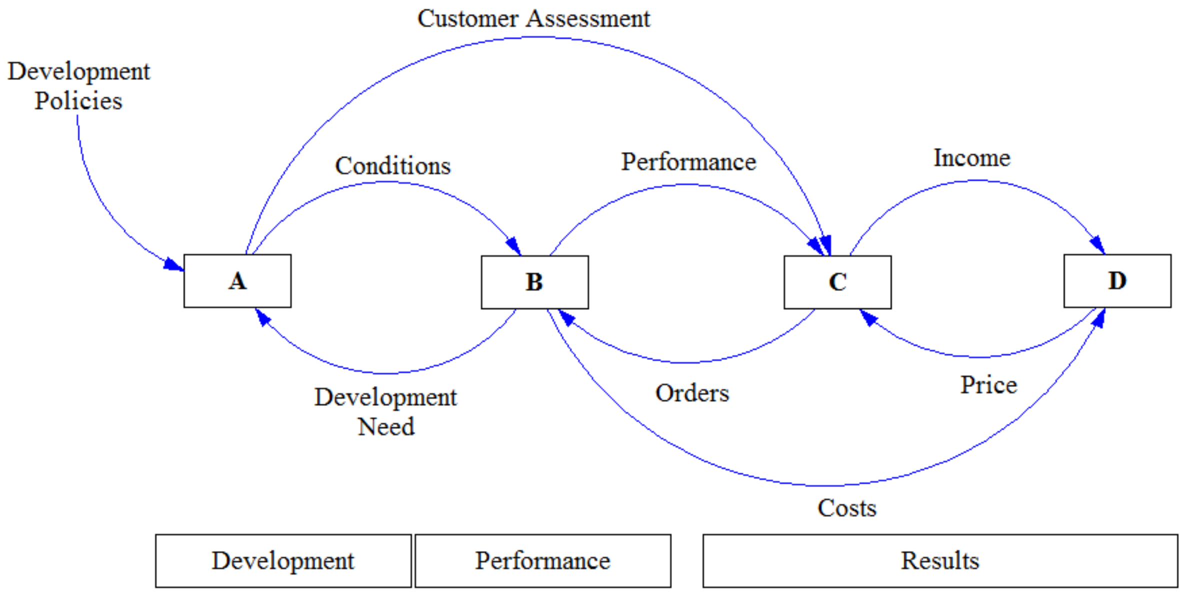

Figure 1. Illustration of the four model parts A,B,C,D featuring key feedbacks

- **A.** Acquisition and Equipment Development Strategy (appendix A)
- **B.** Manufacturing Operations (appendix B)
- **C.** Customer Reaction (appendix C)
- **D.** Flow of Funds (appendix D)

A: Acquisition and Equipment Development Strategy (appendix A)

Purchase and Selling of machines, and the change in Level of Automation (LoA): Purchase of machines depends on ability to identify need of new machines, thus depending on level of Competence and Method. Selling machines are due to machine age and over capacity policies. Largely these in and out flows govern: number of machines and their age structure. Each installation and selling of machines may change LoA, which together with machine ability and MTBF (mean time between failures) result in required level of manpower per runtime. Figure 2 shows how the relation LoA and Manpower is defined; LoA on the X-axis, manual production represents 1 on the scale and 7 represents completely automated equipment.

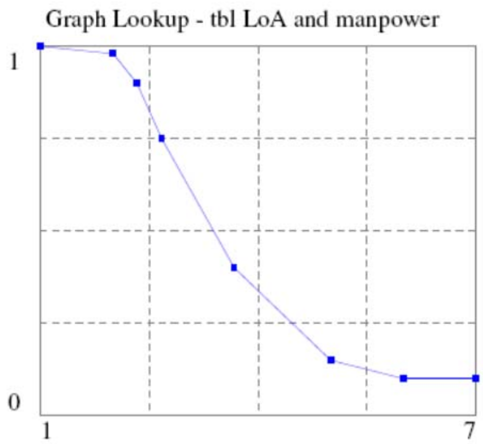

Figure 2. Relation of LoA and Manpower

Development of equipment: Due to maintenance, fixtures, reliable functions, and etcetera. Development of equipment aims to increase machine performance. It is initiated by parameters such as poor process reliability, maintenance costs and ability to identify improvements based on competence.

Implementation of continuous improvements: Improvement projects, they are performed as a consequence of unsatisfying OEE (over all equipment efficiency), Quality performance, level of competence and method, and achieved improvement results. The performance of improvement projects depends on level of competence and methods, previous improvement results and time resources. Improvement projects are goal oriented; at a satisfying level less time is used per improvement. Furthermore, improvement results are continuously degenerated though time delay.

Competence and Method Development (CMD): CMD is important, affecting the time for identifying improvement needs. CMD is governed by size of manpower and the level of competence and method.

B: Manufacturing Operations (appendix B)

Machine performance: Is set to the consequence of machine age, process reliability, level of equipment development, and improvement results. Machine age influences performance; which follows the curve developed in the group modeling session illustrated in figure 3. During year 1 there is an industrialization phase with lower performance, following 5 years in maturity phase performing maximum, after that comes the aging phase with decreasing performance. This curve could be valid when no countermeasures are performed, such as development and preventive maintenance in addition to repairs. This curve is used in the model according to equation (081) in appendix E, also shown below defining the machine age effect.

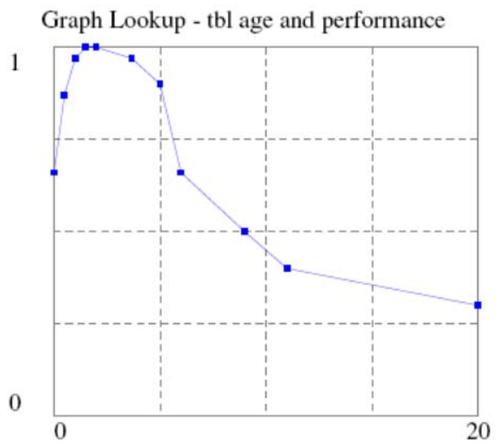

Figure 3. Relation of Age and Performance

Machine Age Effect

$$= \frac{(\text{Industrialisation Phase 1year} \cdot 0.67 + \text{Maturity Phase 5years} \cdot 0.97\,)}{\text{Number of Machines}} + \frac{(\text{Aging Phase 5years} \cdot 0.59 + \text{Sale Phase} \cdot 0.4)}{\text{Number of Machines}} \qquad (081)$$

Using a structure of stocks and flows for including the machine age effect, se appendix A, enables to represent how selling machines affects the machines performance. Those parameters in the numerators in equation (081) above are the stocks multiplied with an arbitrary value for each age group defined with help from the curve in figure 3.

Pieces for sale: Considered the difference between produced pieces and cassations. Process reliability is a central aspect in the system regarding number of pieces produced; it is the product of the machinery age structure, the level of equipment development, and improvement results. Process reliability sets the values of: tact time per piece, machine ability, MTBF, and MTTR (mean time to repair). The lower tact time the more pieces produced. The higher ability the less cassations, the longer MTBF the less stops, shorter downtime, better OEE, and more produced pieces per available runtime.

Summation of costs brought up in the model and their causes:

Level of occupied machines (available runtime in relation to max runtime) is the basis for acquisition of machines. Overtime compensates for delays in that process, which bring an increased cost for manpower. Cassations, a product of machine ability and number of stops, the more stops the greater risk of cassations. Ability is a product of process reliability through a table function similar to figure 2 and 3; shown in equation (151) in appendix E. For example: 100% reliability results in 1000ppm scrap and 80% reliability results in 4000ppm. However, in reality some of the scrap ends at customers and result in customer claims. Thus, the result from cassations is costs and level of quality performance which are interface index parameters to customers in the model. Inventory costs are considered part of delivery performance, costs increase with larger variety of pieces per customer and customer base. However, each new article does not bring a one to one relationship in added costs. This is one side of the effect; purpose with increase in variety of pieces per customer is due to growth, dealt with in part D in the model. Machinery costs are comprised of depreciations and machinery capital interest based on the value of machinery. In decision making sunk costs are often considered, however this model do not consider previous investments. Operator costs are comprised of the direct costs for overtime and manpower. Manufacturing expenses is comprised of direct maintenance costs such as repair time, worn out machine parts, and capital interest from spare part inventory, and direct costs for time spent in development.

C: Customer Reaction (appendix C)

Performance index: Concluding performance measures such as delivery, quality, price, and customer assessment into one index. Each of the three performance measures, delivery, quality, and price, is a function of a table graph with either growth or decline; defined in equation (115) in appendix E. Growth is defined different among the three measures. Delivery performance and quality performance are never better than 100%; maximum performance brings an annual 3% growth. Correspondingly the price index can enable maximum 10% growth. However, at their maximum growth these measures are also dependent on the level of customer assessment, acting as a throttle for the level of growth. As an example does a value of 0.5 in customer assessment reduces the achieved growth from the measures by half.

Growth or decline in turnover of pieces: The change in Customer Base and Variety of Pieces per Customer are depending on the Performance Index; reaction on change is stronger in Variety of Pieces per Customer.

D: Flow of Funds (appendix D)

Summation of funds: Represents how funds flow in and out depending on the current price, manufacturing cost per piece, and turnover of pieces.

Case results

A present state is showed in comparison with six other scenarios. Three variables have been chosen for testing model responses: selling machines policy, competence and method development policy, and LoA policy. How to sell and acquire machines was a question of interest from start. LoA got a more prominent significance during modeling but was also a question from start. CMD (competence) had connections to performing change but was not brought up as a factor from start. Other parameters then these were left unchanged in the model during all simulation runs.

The identified biases of the simulations have been:

- It includes a price policy that may promote growth of turnover of pieces. The implication on simulation is a growing need of machines in itself, thus improving performance automatically. However, using the same policy for all simulations a relative bias exists in all scenario runs.
- The model shows the internally created dynamics over a long time horizon. The modeled system does not consider short term random circumstances, which in reality may cause changes to the dynamics.

In total, the results should be seen as indicators to the consequences of different policies, challenging present mental models of the real system.

Summary on Scenario 1 - 4

Scenario 1. *The present state, including: policy for selling machines from 11 years with 20 months selling process delay, time for CMD set to 4% of manpower, LoA for new equipment according to the relationship that 2 operators can run 5 machines when producing zero stops*. The present state is the Index behavior for analyzing the model dynamics and contrasting the other scenarios. The result parameter Funds in figure 4 shows a neutral behavior in Scenario 1.

Scenario 2. *Policy change for selling machines from 11 years with 20 months selling process delay to a shorter delay of only 3 months:* Shows the most positive development in Funds, figure 4. Comparison between the different scenarios indicate that it is the rejuvenation of machinery that brings better performance, shown by process reliability (figure 9) and machine age effect (figure 8).

Scenario 3. *Time for CMD set to 10% of manpower:* Shows the most negative development in Funds, figure 4. Hence, an increase in CMD did not bring expected improvements as a consequence of higher competence, but resulted in a more responsive and self-improving system. However, it showed more responsive; the oscillation of the system increased, seen in figure 6 with ca3.5 periods for Scenario 3 in the same time span as compared to Scenario 1 with ca2.5. Scenario 3 increased costs (figure 5) mainly due to planned equipment development (figure 7); a consequence of system structure where shorter development time, thanks to increased CMD, identified the need of better equipment faster than it could be implemented through purchase of machines. In total, increasing only CMD did not act on the root cause, indeed increasing the symptom effect of fixing through equipment development.

Scenario 4. *LoA increase 50%, 1 operator per 5 machines:* Each purchase of machines brings better LoA to the machinery, resulting in second best result in Funds, figure 4. However, Scenario 4 shows slightly improved behavior as to Scenario 1, mainly due to less manpower per runtime (figure 11).

Scenario 1-4 simulation experiment graphs

Figure 4 shows the result in Funds; the difference between price to customers and manufacturing cost times turnover of pieces. All scenarios develop similarly during the first 80 months in figure 4 and 5. From then mainly three different behaviors are seen. In Scenario 2 and 4 cost per piece stabilizes (figure 5), partly due to less equipment development in Scenario 2 (figure 7); and lower need of manpower in Scenario 4 due to increased LoA (figure 11).

Figure 6, Scenario 2 results in selling 3 machines initially in a high pace with the consequence of an early need of new machines. A similar behavior is seen in Scenario 3 but later caused by increased ability to identify the need of new machines rather than compensating for lacking machines. Moreover, figure 6 shows that Scenario 4 differs to some extent from Scenario 1.

Figure 7, Scenario 2 shows less development need in planned equipment development due to the rejuvenation of the machinery. Other scenarios show increasing need of development, generating increased equipment cost. Scenario 3 shows an oscillating behavior, due to a more responsive system to changes. Moreover, Scenario 3 behavior commits to increased equipment development even if the result increases costs, lacking reflection on no further gain from development. A behavior in accordance to the real system; seen in the tendency of sub optimizing equipment development.

Figure 10, Scenario 3 results in a rapid decrease in the CMD and IP Index variable. It indicates less need of competence and method development and improvement projects. Scenario 4 develops the least due to that increasing LoA decreases manpower. Scenario 2 in figure 11 shows that selling machines bring less need for manpower due to improved performance of process reliability (figure 9). Scenario 3 in figure 11 shows behavior close to Scenario 1, indicating on no change in manpower from working smarter (CMD).

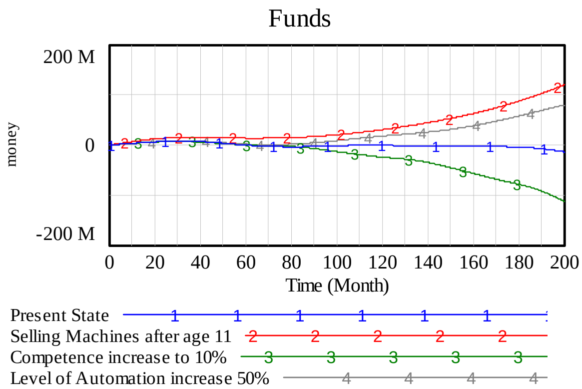

Figure 4. Result in Funds

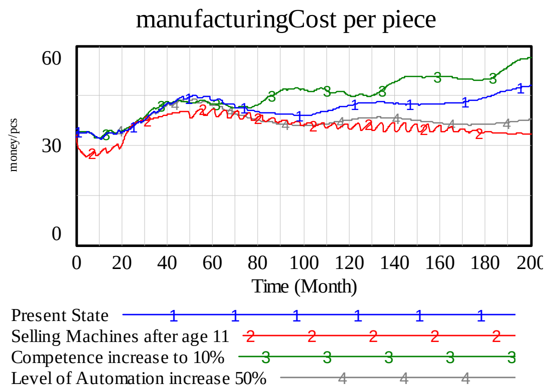

Figure 5. Performance in cost per piece

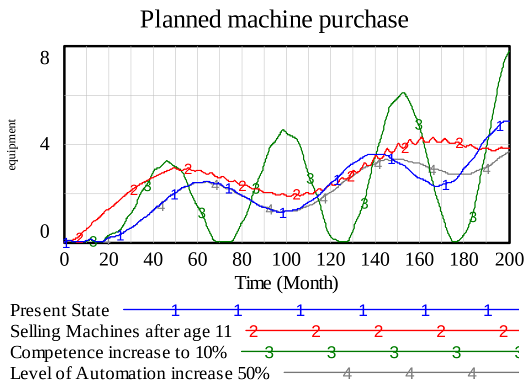

Figure 6. Planned machine purchase

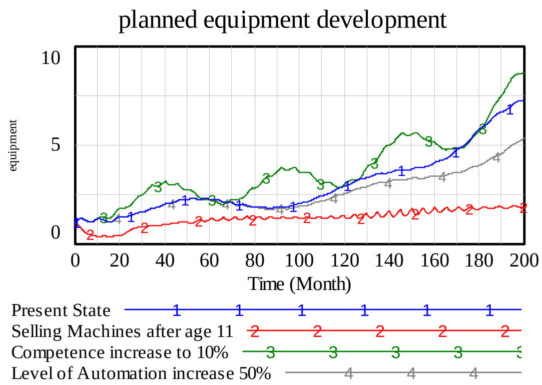

Figure 7. Planned equipment development

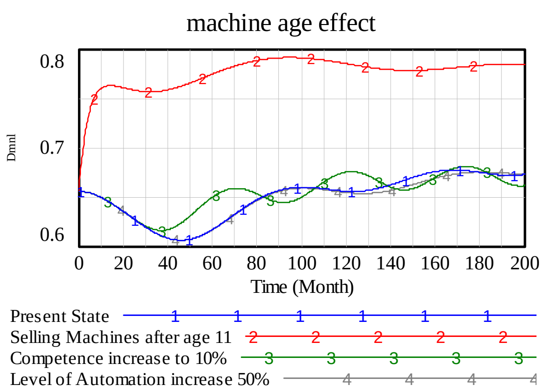

Figure 8. Machine age effect

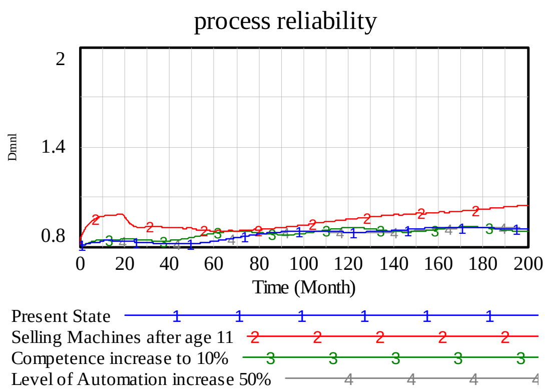

Figure 9. Process reliability

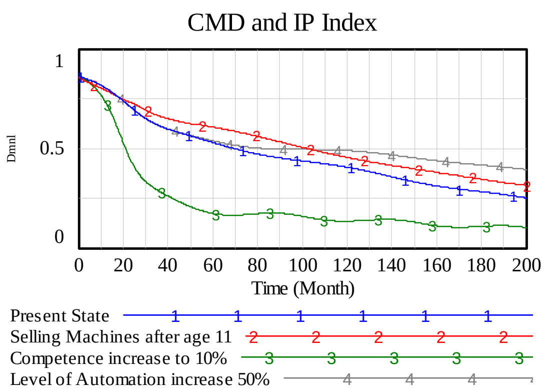

Figure 10. CMD and IP Index

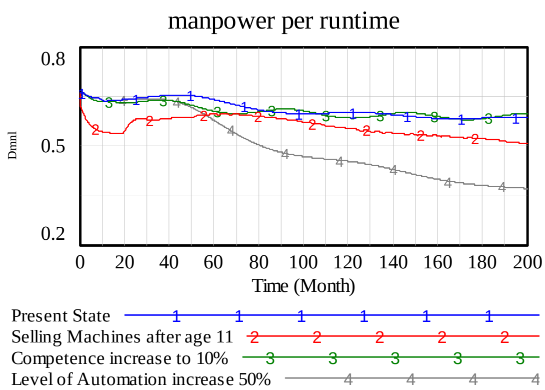

Figure 11. Manpower per runtime

Combination of experiment scenarios

Following experiments was required from the modeling group based on learnings and interest from previous scenarios:

Scenario ES1. Combining Scenario 2, Scenario 3, and Scenario 4 (selling machines at age 11 and 3 months; increase CMD commitment to 10% of manpower; LoA increase by 50%)

Scenario ES2. Combining policies as in ES1, but increase CMD to 20% instead

Scenario ES3. Combining policies as in ES2, but selling machines at age 8 and 3 months

Figure 12 and 13, all three scenarios show similar behavior in both parameters. The results are near three times better than previous best result (compare figure 4 and 12).

Figure 14, the behavior in scenarios (ES1, 2, 3) make the periods of the oscillations shorter and higher compared to previous scenarios. Figure 15, planned equipment development is low for all scenarios.

Figure 16, ES3 brings faster turnover of machines and thus a lower average age, resulting in a higher output in machine age effect. The other two scenarios show a similar behavior. Figure 17 shows a similar behavior for all experiment scenarios.

Figure 18, shows the differences between scenarios in CMD and IP Index; the increase in competence to 20% in ES2 and ES3 show an even more rapid result in bridging the gap of improvements and have durable stable performance. Figure 19, manpower per runtime, shows a similar behavior for all experiment scenarios.

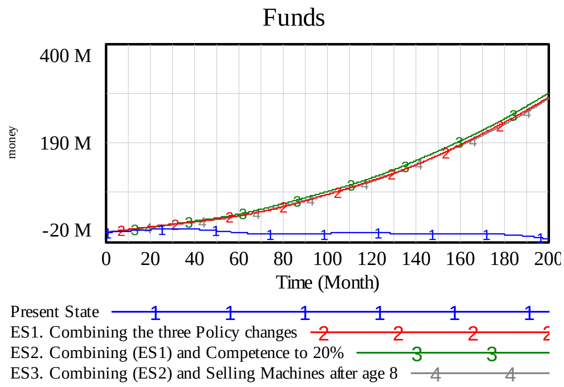

Figure 12. Funds

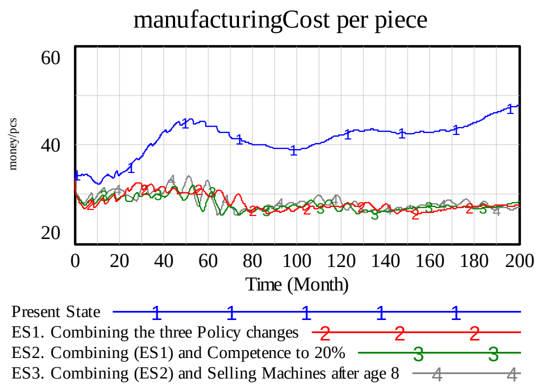

Figure 13. Cost per Piece

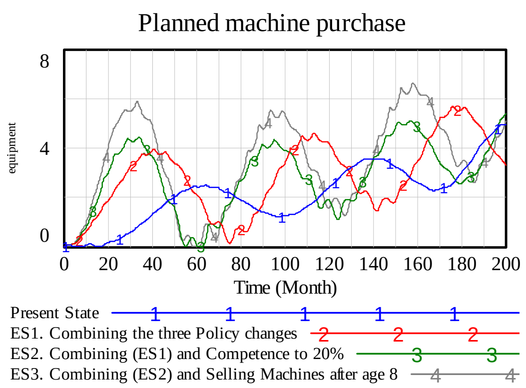

Figure 14. Planned Machine Purchase

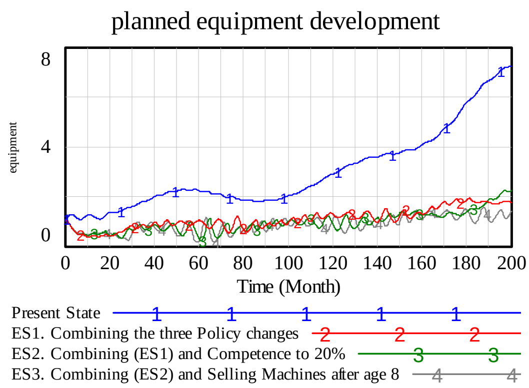

Figure 15. Planned Equipment Development

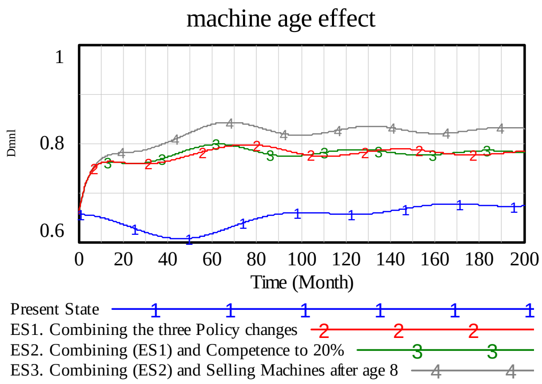

Figure 16. Machine Age Effect

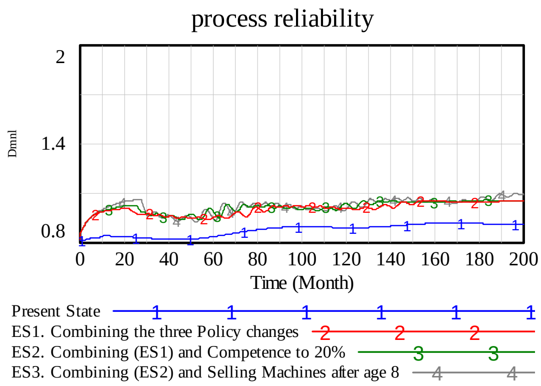

Figure 17. Process Reliability

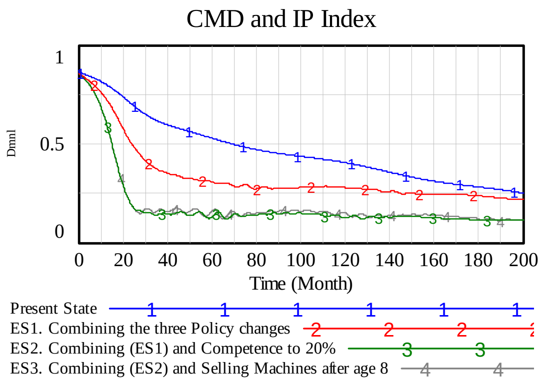

Figure 18. CMD and IP Index

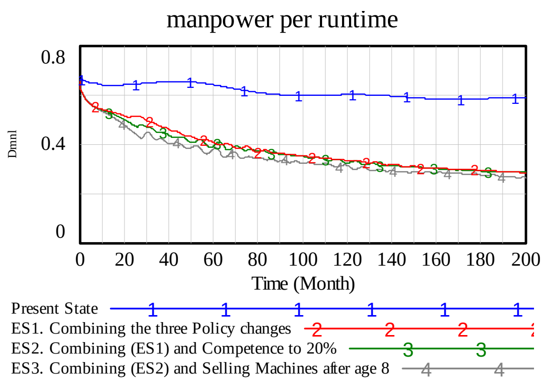

Figure 19. Manpower per Runtime

Conclusion of simulation results

The assumed causes to behavior previous to modeling were: machinery age structure, competence, and automation level. Experiments that improved one parameter at a time showed divided results. However, combining Scenario 2, which had best performance, with increasing CMD commitment in Scenario 3, which had the worst performance, brought together even better results. However, combining all policy changes exposed the best result in the result parameter Funds, see the comparison in figure 20.
Finally, it was considered in the group model building session in which results were presented that further experimentation would be profitable. Emphasizing the potential to bring deeper understanding of consequences from changes, and support identifying proper countermeasures.

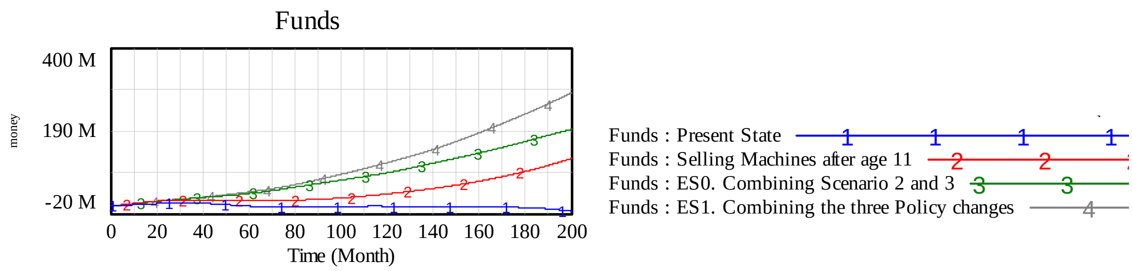

Figure 20. Conclusion of Simulation Results in the Variable Funds

Validation

Validation of system dynamics models requires a number of tests; tests of structure, tests using simulation, and tests for judging the behavior reproduction of the real system (Barlas, 1996). However, validation is a matter of convincement and truthfulness for those people who use a model for support decision making. The validation process is iterative and part of the modeling process. All tests in Sterman (2000) have been performed, and a selection is reviewed here:

Boundary Adequacy: The aim is to include all important parameters from the real system but not too many; the selection of variables define the boundary. And, to greatest extent possible the system should be described using parameters that internally or endogenously create the problematic behavior of the system.

Structure Assessment: The model should be in accordance with the real system. Some decision rules in the model, described in this paper, are interpretations of the real system: because they are not explicitly represented in a real system. Variables of such kind are: how to identify the need of equipment development; and how to identify the need of CMD. The structure test was made in the modeling group; see below.

Parameter Assessment: Judge if all parameters have a real counterpart; all parameters in model do. Although some is undefined in the real system, therefore based on interpretation of causality, this is valid for: process reliability, level of equipment development, and performance Index.

Extreme Conditions: Equation formulation procedure has assured correct values in extreme conditions. The dynamical extreme condition tests did not thoroughly examine each equation, but eliminated exposed incorrect behaviors during modeling and extreme condition tests.

Family Member: Model generality, it is possible to adapt the model to mirror other parts of the same system through adjusting parameters. These generic dynamics of the real system is represented in the model and can be learned from. However, it would be unwise to claim that such general dynamics can be applied directly. There is always a need of soundness judging simulation compared to reality.

Sensitivity Analysis: Three categories of tests: numerical, behavioral, and policy sensitivity. Group model building mainly focuses on behavior and policy sensitivity. Manual behavioral sensitivity tests supported calibrating the model; especially how machine ability cause quality performance and how quality levels result from adding feedbacks to initiate improvement projects.

Some of the tests in the validation process (Sterman, 2000, p. 858-891) require client interaction on the results of modeling and simulation. The real studied system was known by project members but was unidentified in terms of a dynamic system prior to this project. No routines or descriptions existed to inform the total structure of the system. Some parts were familiar to the group members, other parts not thought of before. Modeling brought a collective view upon the elements of Machine Strategy not previously formalized in a total and systematic view like this. The result from validation tests where client evaluates the model were as follows:

Structure Assessment: Positive responses to that the model demonstrates how the real system is considered to be structurally comprised; including causal relations and decision rules.

Behavior Reproduction: Qualitatively the model shows the behavior of the real system. Quantitatively the behavior graphs indicate on a similar behavior as experienced or assumed from the real system. The system problem symptoms were somewhat ambiguous at the start, however, modeling brought clarity to them. Before the modeling project the problem was: aging machinery with its consequences – we need to know the path out from present state. After the project, near all team members thought the outcome of the model was expected. Since the model showed a previously unidentified system and it was difficult to validate if all various modes of real system behavior (Sterman, 2000) were included. All states of the system could not be tested, requiring much more time for experimenting. Evaluation of how well the model reproduced the behavior had answers ranging from doubtful to agreeable on an aggregated level among project members. However, all but one participant thought that the model reproduced behavior of the system of interest.

Surprise Behavior: This test is passed when model shows a previously unrecognized behavior that can be defined part of the real system. This test is difficult, requiring much time for model experimentation and well documented participant mental models prior to modeling, which were poorly mapped in this case due to lack in knowledge. The researcher that performed initial interviews focused more on generating information than modeling mental models. However, interviews provided guidance on prior participant mental models; identified as thinking more linear and in events not grasping a holistic picture. When modeling came into being these events were put into patterns. Two persons responded that the model generated previously unobserved behavior: one of them reflected that modeling provided a feedback system where all parts interrelated for him previously unobserved; the other was challenged in his thinking of how the effects in the total system from certain variables differed from his previous perception.

System Improvement: Consider consequences from modeling with respect to the real system. This case study was delimited not to include implementation of modeling results. However after modeling, the project was considered to facilitate future changes for improvement by the client. The model was considered providing insights for future decision making; "-with reservation, the model provides an indication I can agree upon on an aggregated level". Two of the group members thought that the model could not be used. Another of the group members partly agreed saying: "-yes, it can be used as decision support but it requires more experimenting to achieve a correct informed decision". The results indicate on that, even if it can be difficult to comprehend a new way of thinking (system dynamics using group model building) it provided use to the group, on a personal level for 6 out of 7, and collective group level for 6 out of 7.

Discussion

Applying group model building in system dynamics projects bring about possibilities for better informed decision making. The discussion is structured around the following questions 1-3.

1. *Evaluate if the group members consider themselves have attained learning about the modeled system.*

According to interview results modeling brought learning for 4 of 7 participants, such as: modeling supported thinking of the real system; the discussions increased thinking holistically; and showed the consequences of thinking holistic.

Further, participants answered that this experience may bring learnings for future improvement, such as: learned to consider more parameters in a future decision than thought of previously; we have got a concluding model based on our theories providing us with guidelines for motivating change; learned considering soft parameters and experienced them important in this modeling, therefore they should be considered more in future than previously done.

The evaluation categorized learning into three processes:

a) The process of modeling;

b) The approach to a problem situation (process of thinking of consequences over time);

c) The process of reviewing simulation results in group discussions.

How these processes felt rewarding for learning were graded 1-3 by the respondents, resulting in a grade for each process: a) 1.7; b) 1.9; c) 2.4. Process a) and b) were graded similarly, with a clear gap to c). One participant clearly pointed item c) as the most rewarding process, with the explanation that it was not until then the complete puzzle of the methodology could be seen for him.

Reflections: difficult with non-quantifiable parameters; system dynamics differ compared to previous experienced tools by including more soft parameters; analysis would have profit from more experimentation; utilizing system dynamics illuminates that it exist unaware aspects in previously known systems; and that the project provided a good discussion basis.

2. *Evaluate the group members' view on model results, regarding: validity, use, and as decision base for future implementation.*

The validity tests (Sterman, 2000) all showed positive results besides for: *Surprise Behavior* and *System Improvement.* Both would benefit from more group model building sessions in order to: increase understanding of previously unknown system behaviors; and increase confidence for system improvement actions. Most participants positively responded to if the modeling process would facilitate future improvement. Important for validity is participants' view upon model results, this was perceived twofold. In one hand: the model shows behavior of the system of interest (6 of 7); may on an aggregated level work as decision basis (5 of 7); the results were almost known beforehand (4 of 7). And in the other hand: the modeling showed no better than gut feeling, or cannot trust model results there are too many uncertain parameters. However, 6 of 7 considered the modeling effort to be fruitful and worth performing.

3. *Compare the responses on model results in this case to a previous modeling case, by (Linnéusson et al., 2008), where group model building was not utilized.*

The comparison with a previously made case study (Linnéusson et al 2008) is presented in order to explicitly show how two studies were received in the client organization. The previous case study applied system dynamics for problem understanding on a manufacturing issue; Tool Data Management (TDM). That study did not focus on client responses on model results. However, as an industrial PhD candidate, the researcher was part of the environment in which the study was conducted and thereby able to present aspects of interest. In the TDM case study the results were presented two times, for persons from preparation and production engineering, CEO, and a management team member. Both times clients showed interest and agreed that model applied to reality. However, it did not result in clear commitment for future work, even though the model highlighted problems in a present system of interest. Bias information regarding the first case study is that it was initiated by the researcher, who observed an urgent problem for the organization suitable for system dynamics modeling. Thus, it was not based on a demand from the organization, which may affect commitment. Modeling used a traditional approach where the modeler collected data from the organization and put into model, interpreting achievement of acceptable results; a process excluding the organization from constructing user confidence during modeling as in for instance group model building. Altogether these aspects affect the level of response on the results. However, the study focus was on exploring applicability of system dynamics for a manufacturing problem, which was considered successfully attained.

On the other hand, the group model building approach, presented in this paper, showed larger engagement and commitment for the case results. Comparison between cases indicates group model building being a crucial factor for the level of response on the results. The identified advantages with group model building are: better pre condition for unity on problem content and boundary, better basis for eliciting model data since model building was performed together with client; better development of common mental models; discussions brought up not previously held system of interest discussions; client is better informed for future system improvements since all group members have been more active in the learning of the system of interest.

System dynamics lack guidelines for implementing a project and especially for manufacturing systems development. Moreover, deep knowledge and habit is required from the facilitator/model builder in order to control the group model building process. Improved guidelines for such projects may thus positively affect its utilization.

Time is always an issue of interest during a project. Time to develop a model did not restrain the progress of the real world problem. However evaluation identified the project to have profited from using more time for experimenting. Model experimentation was mainly characterized of presenting simulation results. It was unsatisfying; however the proper solution regarding managing the project in time. It is worth to further consider how to improve model experimentation for future projects.

Conclusions

This study describes a group model building project performed at a Swedish manufacturer in Sweden, studying the behavioral dynamics of Machine Strategy effects on a general level. It includes: policies governing machine aging, development of equipment, level of automation, competence and method development, and improvement work, and how these parameters affect the production system of a certain boundary including internal feedback and some customer perspectives.

The modeling participants verify that the model includes a proper boundary and that it contributes to future implementations; however there are also at the same time reservations on using the attained results. In order to increase alignment it is identified that more efforts in experimentation and complementary modeling would have been profitable.

Group model building brings added value to system dynamics for manufacturing systems development compared to the traditional modeling approach. However using system dynamics projects in manufacturing is not a straightforward process and would improve by a framework of guidelines for implementing such projects.

The case study shows that such framework would benefit from the inclusion of group model building and guidelines for how to implement a project.

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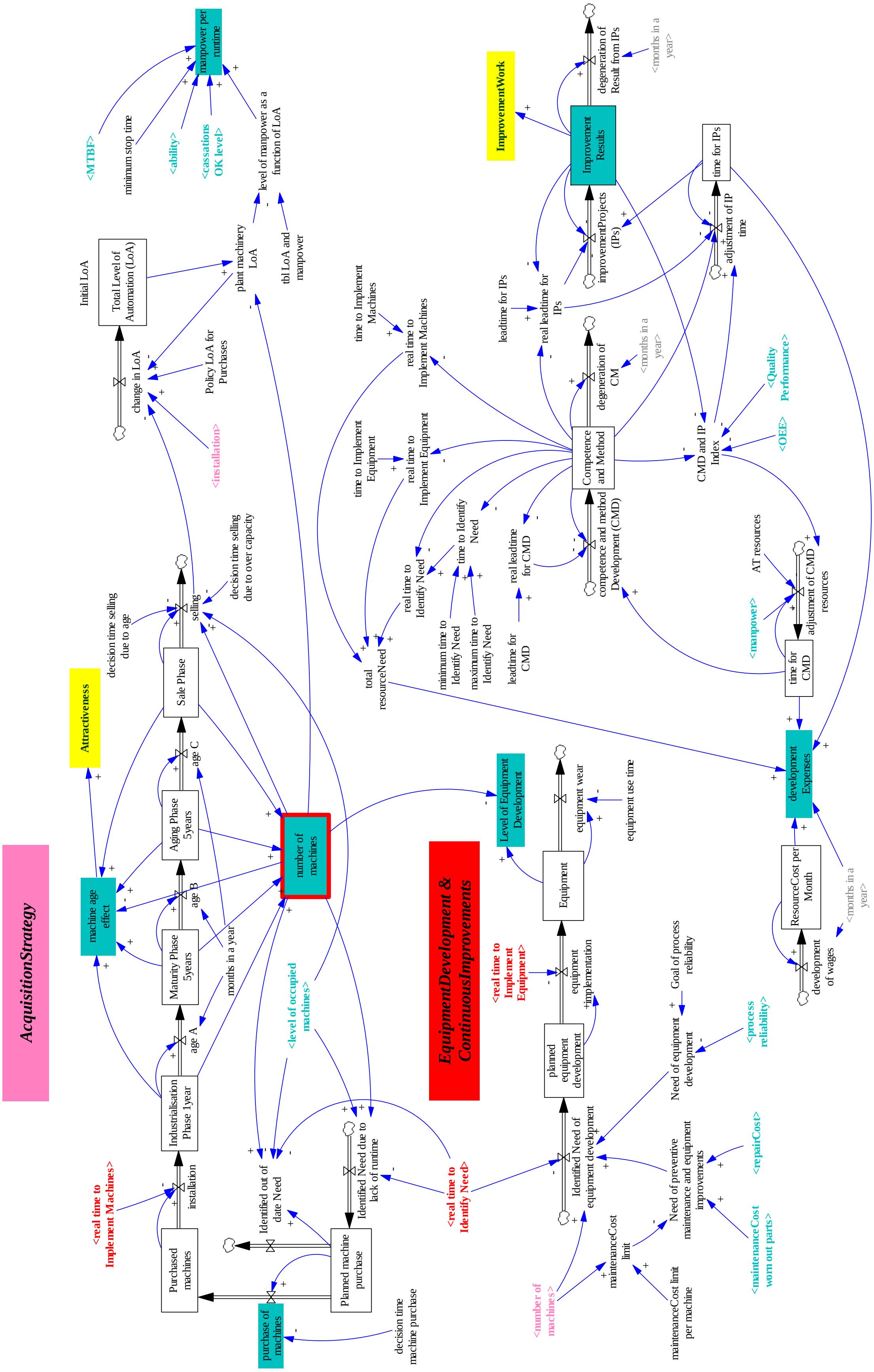
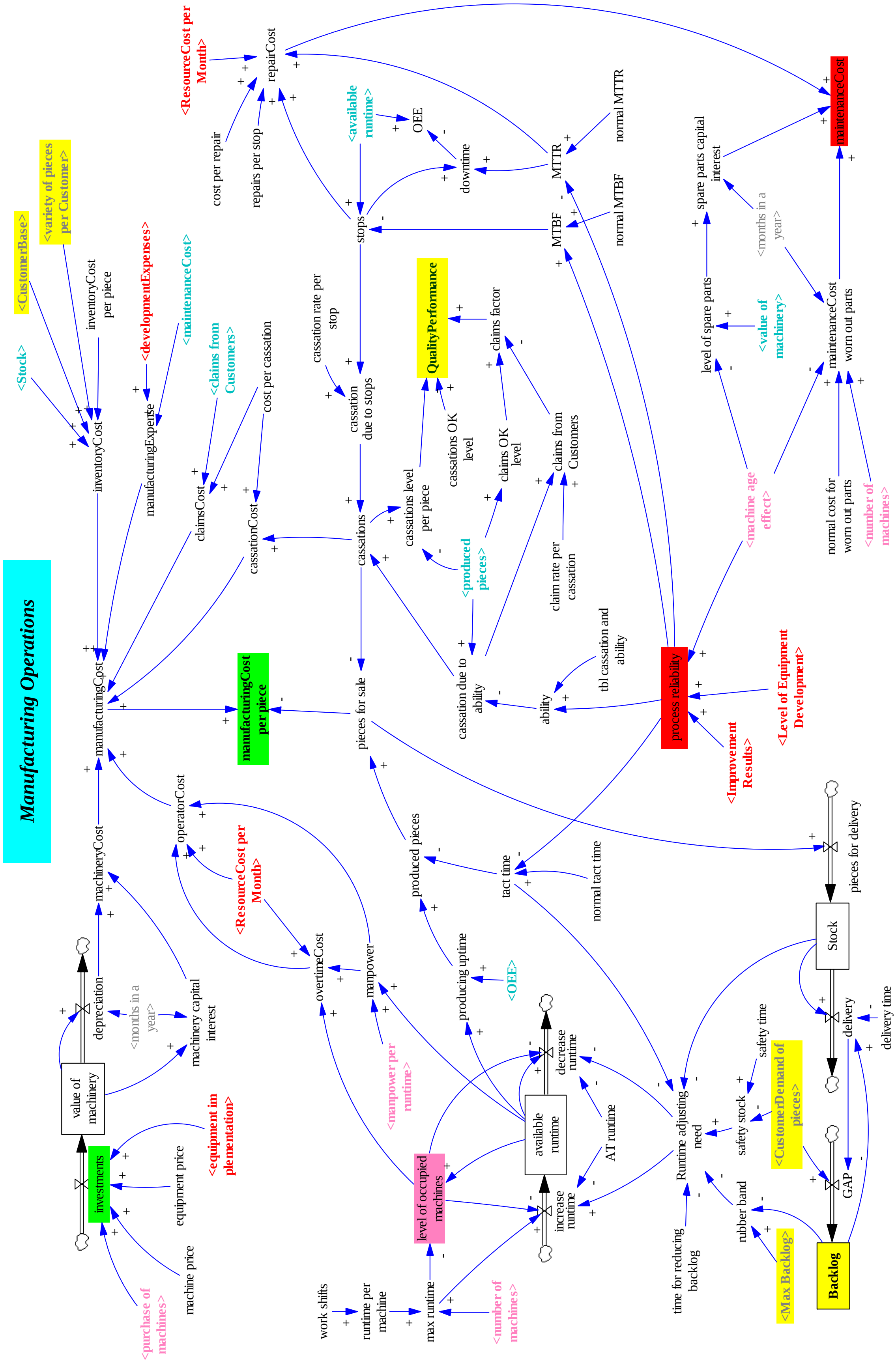
Appendix A



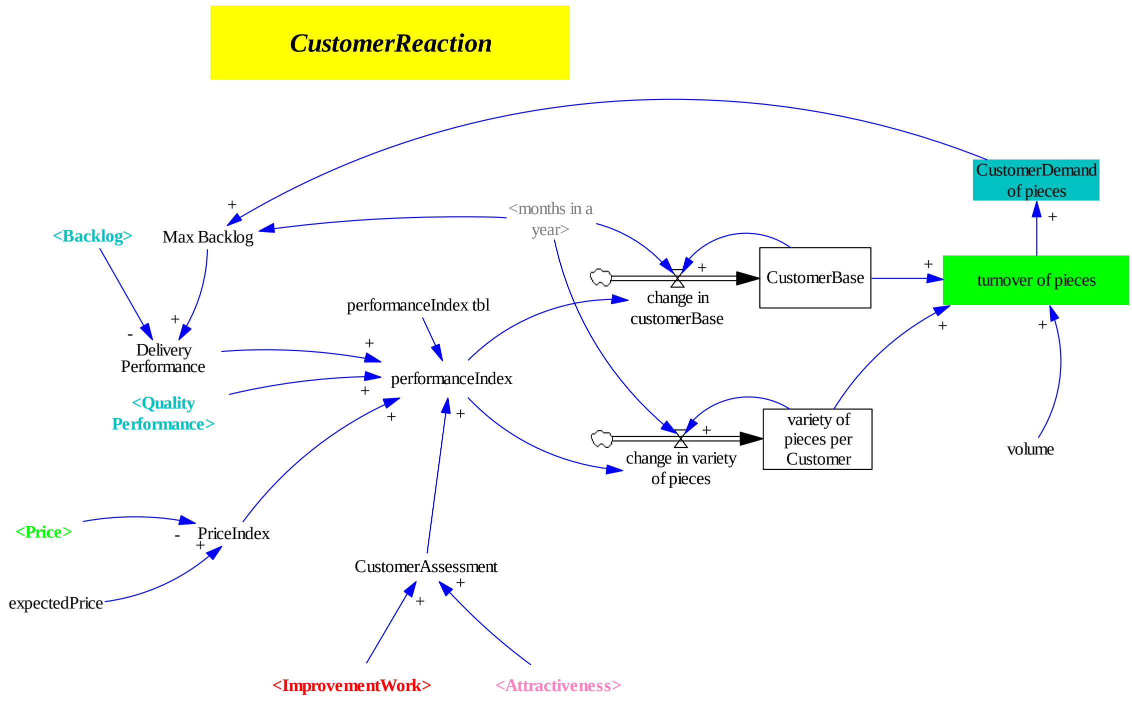
Part 1. Acquisition and Equipment Development Strategy

Appendix B



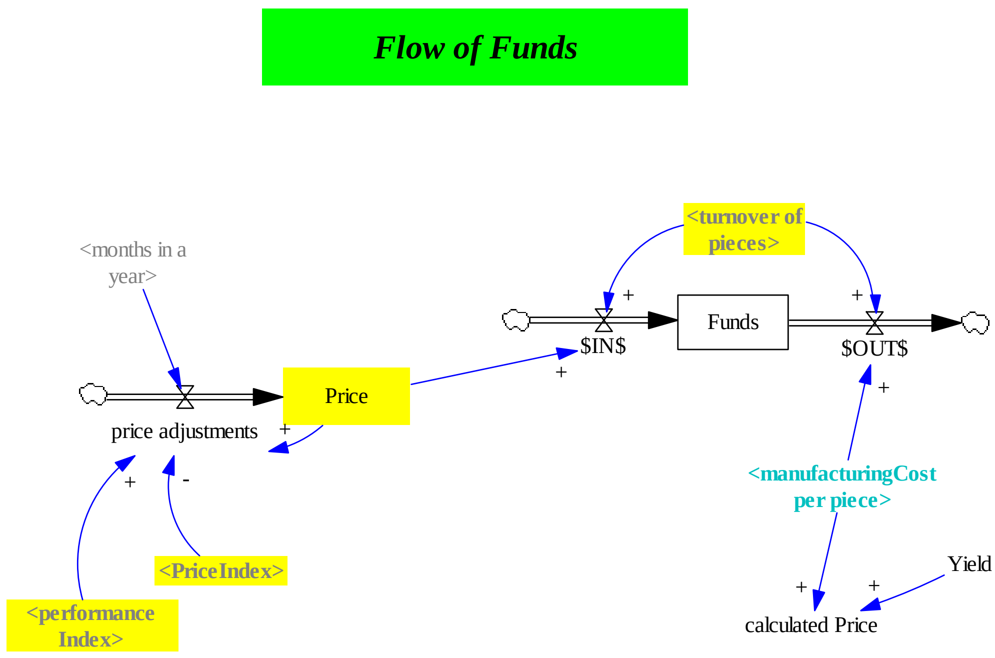
Part 2. Manufacturing Operations

Appendix C



Part 3. Customer Reaction

Appendix D



Part 4. Flow of Funds

Appendix E: Model equations

(001) "IN"=Price * turnover of pieces Units: money/Month

(002) "OUT"=manufacturingCost per piece * turnover of pieces Units: money/Month

(003) ability=tbl cassation and ability(process reliability) Units: Dmnl

(004) adjustment of CMD resources=(0.04 * manpower - time for CMD) * CMD and IP Index / AT resources Units: Dmnl/Month

Adjustment size is decided by: maximum resource level (policy ruled % of manpower) and is not exceeded, the development need, and adjustment time (AT).

(005) adjustment of IP time=MAX(0, (CMD and IP Index - (1-Competence and Method))) / real leadtime for IPs + IF THEN ELSE(time for IPs > 0.01 :AND: CMD and IP Index < (1 - Competence and Method), (CMD and IP Index - (1 - Competence and Method)) / real leadtime for IPs, 0) Units: Dmnl/Month

Adjustment of IP time is goal oriented, the level of competence filter size of development need; first part of equation is adding time, second part taking time out.

(006) age A=Industrialisation Phase 1year / months in a year Units: equipment/Month

(007) age B=Maturity Phase 5years / (months in a year * 5) Units: equipment/Month

(008) age C=Aging Phase 5years / (months in a year * 5) Units: equipment/Month

(009) Aging Phase 5years= INTEG (age B-age C,3) Units: equipment

(010) AT resources=3 Units: Month

(011) AT runtime=3 Units: Month

(012) Attractiveness=MIN(machine age effect, 0.67) / 0.67 Units: Dmnl

(013) available runtime= INTEG (increase runtime-decrease runtime,max runtime) Units: months/Month

(014) Backlog= INTEG (GAP,10000) Units: pcs

(015) calculated Price=manufacturingCost per piece * Yield Units: money/pcs

(016) cassation due to ability=produced pieces * ability Units: pcs/Month

(017) cassation due to stops=stops * cassation rate per stop Units: pcs/Month

(018) cassation rate per stop=0.05 Units: pcs/stop

(019) cassationCost=cassations * cost per cassation Units: money/Month

(020) cassations=cassation due to ability + cassation due to stops Units: pcs/Month

(021) cassations level per piece=cassations / MAX(cassations, produced pieces) Units: Dmnl

(022) cassations OK level=0.00475 Units: Dmnl

*The ok level represents ca0.67 in machine age effect in the ability graph (4000ppm) and 750ppm from cassations from stops at (0.67 * 1.25 * 1.03) see equation of process reliability.*

(023) change in customerBase=CustomerBase * (performanceIndex - 10) / (months in a year * 10 * 4) Units: customers/Month

(024) change in LoA=installation * Policy LoA for Purchases - selling * plant machinery LoA Units: LoA/Month

(025) change in variety of pieces=variety of pieces per Customer * (performanceIndex - 10) / (months in a year * 10 * 2) Units: categories/(Month*customer)

(026) claim rate per cassation=0.02 Units: Dmnl

(027) claims factor=MIN(claims OK level / MAX(1, claims from Customers), 1) Units: Dmnl

(028) claims from Customers=cassation due to ability * claim rate per cassation Units: pcs/Month

(029) claims OK level=produced pieces * 200 / 1e+006 Units: pcs/Month

(030) claimsCost=claims from Customers * 100 * cost per cassation Units: money/Month

A claimCost is identified 100 times more expencive then a cassationCost.

(031) CMD and IP Index=MAX(-1, 1 - MAX(0, OEE / 0.85 * QualityPerformance * Competence and Method / 0.85 * Improvement Results / 0.85)) Units: Dmnl

(032) Competence and Method= INTEG ("competence and method Development (CMD)"-degeneration of CM,0.4) Units: Dmnl

(033) "competence and method Development (CMD)"=(1 - MIN(Competence and Method, 1)) * time for CMD / real leadtime for CMD Units: Dmnl/Month

(034) cost per cassation=300 Units: money/pcs

(035) cost per repair=10000 Units: money / repair

(036) CustomerBase= INTEG (change in customerBase,20) Units: customers

(037) CustomerDemand of pieces=turnover of pieces Units: pcs/Month

(038) decision time machine purchase=18 Units: Month

(039) decision time selling due to age=120 Units: Month

(040) decision time selling due to over capacity=120 Units: Month

(041) decrease runtime=IF THEN ELSE(level of occupied machines > 1, MAX(0, -Runtime adjusting need) / (AT runtime * 0.01), MIN(MAX(0, -Runtime adjusting need) / AT runtime , available runtime / AT runtime))
Units: Dmnl/Month

If the level of occupied machines is over 1 decrease runtime can be made directly, if not over 1 adjustment is according to need and delay.

(042) degeneration of CM=0.2 * Competence and Method / months in a year Units: Dmnl/Month
20 % of competence is not used daily and forgotten within a year

(043) degeneration of Result from IPs=0.8 * Improvement Results / months in a year Units: Dmnl/Month
80% of the improvement work is not lasting and gone within a year

(044) delivery=MIN(Backlog/delivery time, Stock/delivery time) Units: pcs/Month

(045) delivery time=24/492 Units: Month
*daily delivery in months, every 24 hours per operating day (492=24h*20.5days)*

(046) DeliveryPerformance=MIN(Max Backlog/Backlog, 1) Units: Dmnl

(047) depreciation=value of machinery * 0.2/months in a year Units: money/Month

(048) development of wages=ResourceCost per Month * 0.03 / months in a year Units: money/Month/Month

(049) developmentExpenses=(ResourceCost per Month * total resourceNeed) / months in a year + ResourceCost per Month * (time for CMD + time for IPs) Units: money/Month

(050) downtime=MAX(0.01, stops * MTTR) Units: months/Month

(051) Equipment= INTEG (equipment implementation-equipment wear,number of machines * 1.2)
Units: equipment

(052) equipment implementation=planned equipment development / real time to Implement Equipment
Units: equipment/Month

(053) equipment price=500000 Units: money/equipment

(054) equipment use time=2 * 12 Units: Month

(055) equipment wear=Equipment / equipment use time Units: equipment/Month

(056) expectedPrice=46 Units: money/pcs

(057) FINAL TIME = 200 Units: Month
The final time for the simulation.

(058) Funds= INTEG ("IN"-"OUT",0) Units: money

(059) GAP=CustomerDemand of pieces - delivery Units: pcs/Month

(060) Goal of process reliability=1 Units: Dmnl

(061) Identified Need due to lack of runtime=MAX(0, IF THEN ELSE(level of occupied machines > 0.95, ((level of occupied machines-0.95)*number of machines) / real time to Identify Need, 0)) Units: equipment/Month

(062) Identified Need of equipment development=(Need of preventive maintenance and equipment improvements * Need of equipment development - 1) * number of machines / real time to Identify Need Units: equipment/Month
A situation of aged machines create a larger demand then necessary as a symptom of a low process reliability.

(063) Identified out of date Need=IF THEN ELSE(level of occupied machines < 0.95 :AND: Planned machine purchase > 0.01, (0.95 - level of occupied machines) * number of machines / real time to Identify Need, 0)
Units: equipment/Month

When level of occupation is below 0.95 the plans of machine purchase are deleted.

(064) Improvement Results= INTEG ("improvementProjects (IPs)"-degeneration of Result from IPs,0.3)
Units: Dmnl

(065) "improvementProjects (IPs)"=(1 - MIN(Improvement Results, 1)) * time for IPs / real leadtime for IPs
Units: Dmnl/Month

(066) ImprovementWork=Improvement Results/0.85 Units: Dmnl

(067) increase runtime=MIN(MAX(0, Runtime adjusting need) /AT runtime , ((1.35 - level of occupied machines) * max runtime / AT runtime)) Units: Dmnl/Month

1.35 is a possible extension of over time work hours.

(068) Industrialisation Phase 1year= INTEG (installation-age A,1) Units: equipment

(069) Initial LoA=3.67 Units: LoA/equipment

(070) INITIAL TIME = 0 Units: Month

The initial time for the simulation.

(071) installation=Purchased machines / real time to Implement Machines Units: equipment/Month

(072) inventoryCost=inventoryCost per piece * Stock * 0.32 * CustomerBase * variety of pieces per Customer Units: money/Month

*20% of the pieces have 80% of the volume flow, the other 20% have a low flow. (20% * 80% + 80% * 20% = 0.32 equivalent to ca 3 in total inventory turnover)*

(073) inventoryCost per piece=0.5 Units: money/(Month*pcs*category)

*60 money * 10% interest / 12 months = ca 0.5*

(074) investments=purchase of machines * machine price + equipment implementation * equipment price Units: money/Month

(075) leadtime for CMD=5 Units: Month

(076) leadtime for IPs=2 Units: Month

(077) Level of Equipment Development=MIN(Equipment / number of machines , 1.25) Units: Dmnl

(078) level of manpower as a function of LoA=tbl LoA and manpower(plant machinery LoA) Units: Dmnl

(079) level of occupied machines=MIN(available runtime / max runtime, 1.35) Units: Dmnl

(080) level of spare parts=0.015 * value of machinery * (1 / machine age effect) Units: money

(081) machine age effect=(Industrialisation Phase 1year * 0.67 + Maturity Phase 5years * 0.97 + Aging Phase 5years * 0.59 + Sale Phase * 0.4) / number of machines Units: Dmnl

(082) machine price=3.5e+006 Units: money/equipment

(083) machinery capital interest=0.1 * value of machinery / months in a year Units: money/Month

(084) machineryCost=depreciation + machinery capital interest Units: money/Month

(085) maintenanceCost=maintenanceCost worn out parts + spare parts capital interest + repairCost Units: money/Month

(086) maintenanceCost limit=maintenanceCost limit per machine * number of machines Units: money/Month

(087) maintenanceCost limit per machine=30000 Units: money/Month/equipment

(088) maintenanceCost worn out parts=(1 / machine age effect * normal cost for worn out parts * number of machines) / months in a year Units: money/Month

(089) manpower=available runtime * manpower per runtime Units: months/Month

(090) manpower per runtime=level of manpower as a function of LoA / ((MTBF / minimum stop time) * MIN((cassations OK level / ability), 1)) Units: Dmnl

(091) manufacturingCost=machineryCost + operatorCost + manufacturingExpense + cassationCost + inventoryCost + claimsCost Units: money/Month

(092) manufacturingCost per piece=manufacturingCost / pieces for sale Units: money / pcs

(093) manufacturingExpense= developmentExpenses + maintenanceCost Units: money/Month

(094) Maturity Phase 5years= INTEG (age A-age B,3) Units: equipment

(095) Max Backlog=0.05 * CustomerDemand of pieces * months in a year Units: pcs

(096) max runtime=number of machines * runtime per machine Units: months/Month

(097) maximum time to Identify Need=10 Units: Month

(098) minimum stop time=8 / 720 Units: Month/stop

(099) minimum time to Identify Need=3 Units: Month

(100) months in a year=12 Units: Month

(101) MTBF=process reliability * normal MTBF Units: Month / stop

(102) MTTR=normal MTTR / process reliability Units: Month/stop

(103) Need of equipment development=Goal of process reliability / process reliability Units: Dmnl

(104) Need of preventive maintenance and equipment improvements=MAX(1, (repairCost + maintenanceCost worn out parts) / maintenanceCost limit) Units: Dmnl

(105) normal cost for worn out parts=50000 Units: money/equipment

(106) normal MTBF=6 / 720 Units: Month/stop
6 hours is a normal that can be boosted by process reliability to a time of 8.25 hours which is exactly enough for running without manpower during a night shift.

(107) normal MTTR=0.87 * 1.1 * 1.25 / 720 Units: Month/stop
0.87 hours represent max performance comprised of 80% 20 minute short stops and 20% 3 hour long stops which require maintenance: (1.1 is max boost from IPs, 1.25 max boost from level of equipment development)

(108) normal tact time=3 / 60 / 720 Units: Month/pcs

(109) number of machines=Industrialisation Phase 1year + Maturity Phase 5years + Aging Phase 5years + Sale Phase Units: equipment

(110) OEE=MAX(0, MIN(1- downtime/ available runtime, 1)) Units: Dmnl

(111) operatorCost=manpower * ResourceCost per Month + overtimeCost Units: money/Month

(112) CustomerAssessment=MIN(ImprovementWork * Attractiveness, 1) Units: Dmnl

(113) overtimeCost=MAX(0, (level of occupied machines - 1) * manpower * ResourceCost per Month * 2.1) Units: money/Month

(114) performanceIndex=MAX(0.01, 10 * MIN(performanceIndex tbl(DeliveryPerformance) * performanceIndex tbl(QualityPerformance) * performanceIndex tbl(PriceIndex), (1 + 0.1*CustomerAssessment))) Units: Dmnl
10 is the normal of the index, limits to growth is ruled by the customer assessment with a maximum of 10% annually growth.

(115) performanceIndex tbl([(0,0)-(1.1,2)],(0,0),(0.3,0.09),(0.4,0.16),(0.5,0.25),(0.6,0.36),(0.7,0.49),(0.8,0.64),(0.9,0.81),(0.99,1),(1,1.03),(1.05,1.08),(1.1,1.1)) Units: Dmnl

(116) pieces for delivery=pieces for sale Units: pcs/Month

(117) pieces for sale=MAX(1, produced pieces - cassations) Units: pcs/Month

(118) planned equipment development= INTEG (Identified Need of equipment development-equipment implementation, number of machines*0.1) Units: equipment

(119) Planned machine purchase= INTEG (Identified Need due to lack of runtime-Identified out of date Need-purchase of machines,0) Units: equipment

(120) plant machinery LoA=MAX(1, MIN("Total Level of Automation (LoA)" / number of machines, 7)) Units: LoA/equipment

(121) Policy LoA for Purchases=3.67 Units: LoA / equipment

(122) Price= INTEG (price adjustments, calculated Price) Units: money/pcs

(123) price adjustments=IF THEN ELSE(performanceIndex > 10.5, (10 / performanceIndex) * 0.01*Price / months in a year, - IF THEN ELSE(PriceIndex < 1.1, (10 / performanceIndex) * 0.1*Price / months in a year, 0)) Units: money/(Month*pcs)

(124) PriceIndex=MIN(expectedPrice / MAX(0.01, Price), 1.1) Units: Dmnl

(125) process reliability=machine age effect * Level of Equipment Development * (1 + 0.1* Improvement Results) Units: Dmnl

(126) produced pieces=producing uptime / tact time Units: pcs/Month

(127) producing uptime=available runtime * OEE Units: months/Month

(128) purchase of machines=Planned machine purchase / decision time machine purchase Units: equipment/Month

(129) Purchased machines= INTEG (purchase of machines-installation,0) Units: equipment

(130) QualityPerformance=MIN(cassations OK level / cassations level per piece, 1) * claims factor Units: Dmnl

(131) real leadtime for CMD=leadtime for CMD / Competence and Method Units: Month

(132) real leadtime for IPs=leadtime for IPs / (Competence and Method * Improvement Results) Units: Month

(133) real time to Identify Need=time to Identify Need / Competence and Method Units: Month

(134) real time to Implement Equipment=time to Implement Equipment / Competence and Method Units: Month

(135) real time to Implement Machines=time to Implement Machines / Competence and Method Units: Month

(136) repairCost=stops * (repairs per stop * cost per repair + MTTR*0.69 * ResourceCost per Month) Units: money/Month

0.69 of stop time requires maintenance the other stops are managed by operators, calculated as 20% of stops take 3 hours per stop and require maintenance and other 80% of stops take 20min per stop.

(137) repairs per stop=0.01 Units: repair / stop

(138) ResourceCost per Month= INTEG (development of wages,400 * 20.5 * 24) Units: money/Month

(139) rubber band=Max Backlog-Backlog Units: pcs

(140) Runtime adjusting need=(safety stock - MAX(0, rubber band)- Stock) * tact time / time for reducing backlog Units: months/Month

(141) runtime per machine=work shifts * 8 * 20.5 / 720 Units: Month / equipment / Month
*(shift * hours per shift * days per month / hours in a month)*

(142) safety stock=safety time * CustomerDemand of pieces Units: pcs

(143) safety time=0.5 Units: Month

(144) Sale Phase= INTEG (age C-selling,3) Units: equipment

(145) SAVEPER = 0.25 Units: Month [0,?]
The frequency with which output is stored.

(146) selling=Sale Phase / decision time selling due to age + MIN(MAX(0, 0.7 - level of occupied machines) * number of machines / decision time selling due to over capacity, Sale Phase / decision time selling due to over capacity) Units: equipment/Month

(147) spare parts capital interest=level of spare parts * 0.1 / months in a year Units: money/Month

(148) Stock= INTEG (pieces for delivery-delivery,0) Units: pcs

(149) stops=available runtime / MTBF Units: stop / Month

(150) tact time=normal tact time* ((1/process reliability-1)/5+1) Units: Month /pcs

(151) tbl cassation and ability([(0,0)-(1.4,1)],(0,1.024),(0.2,0.256),(0.4,0.064),(0.5,0.032),(0.6,0.016), (0.7,0.008),(0.8,0.004),(0.9,0.002),(1,0.001),(1.4,0.0004)) Units: Dmnl

(152) tbl LoA and manpower([(1,0)-(7,1)],(1,1),(2,0.98), (2.33,0.9),(2.67,0.75),(3.67,0.4),(5,0.15),(6,0.1),(7,0.1)) Units: Dmnl

(153) time for CMD= INTEG (adjustment of CMD resources,0.1 * manpower) Units: months/Month

(154) time for IPs= INTEG (adjustment of IP time,0.1 * manpower) Units: months/Month

(155) time for reducing backlog=0.5 Units: Month

(156) TIME STEP = 0.0078125 Units: Month [0,?]
The time step for the simulation.

(157) time to Identify Need=MAX(minimum time to Identify Need, maximum time to Identify Need * (1-Competence and Method)) Units: Month

(158) time to Implement Equipment=1 Units: Month

(159) time to Implement Machines=3 Units: Month

(160) "Total Level of Automation (LoA)"= INTEG (change in LoA, Initial LoA * number of machines) Units: LoA

(161) total resourceNeed=0.2* real time to Identify Need + 0.2 * (real time to Implement Equipment + real time to Implement Machines) Units: Month
The time need of resources is simplified to be 0.2, this does not consider amount of projects.

(162) turnover of pieces=MAX(0.001 , CustomerBase * variety of pieces per Customer * volume) Units: pcs/Month

(163) value of machinery= INTEG (investments-depreciation,(1*3.15e+006 + 3*1.8e+006 + 3*1e+006 + 3*0) * (1 + 1/7)) Units: money

The initial value is based on the division of machines in the age categories and depreciations, start value for equipment is 1/7th of that for value of machinery.

(164) variety of pieces per Customer= INTEG (change in variety of pieces, 3) Units: categories/customer

(165) volume=1000 Units: pcs/category/Month

(166) work shifts=3 Units: Dmnl/equipment

(167) Yield=1.15 Units: Dmnl