Maintenance performance improvement with System Dynamics:

A Corrective Maintenance showcase

R.E.M. Deenen[1,2], C.E. van Daalen[1] and E.G.C. Koene[2]
[1] Delft University of Technology, Faculty of Technology, Policy and Management
P.O. Box 5015, 2600 GA Delft, The Netherlands
[2] Accenture BV, P.O. Box 75797, 1070 Amsterdam, The Netherlands
e-mail: rutger.deenen@accenture.com; c.vandaalen@tudelft.nl

Abstract

This paper presents a case study of an analysis of a Corrective Maintenance process to realize performance improvement. The Corrective Maintenance process is supported by SAP, which has indicated the performance realisation problem. System Dynamics is used in a Group Model Building process to structure the problem and to develop a dynamic business model with which the process is analysed. This is performed by the evaluation of changes in external factors and interventions in the process on performance indicators compared to a reference run. The case study has shown that modelling this maintenance performance problem is possible with System Dynamics, but the method is more suitable on an aggregated level. Although the results of this simulation study are significant, one of the conclusions is to not automatically assume that System Dynamics is suitable for problems that are structured with Group Model Building. It is recommended to select another modelling method after the problem is structured, if that method is more suitable.

Keywords: Corrective Maintenance, Performance, SAP, System Dynamics, Group Model Building

Introduction

The maintenance process, as a supportive function to keep the production processes operational, has changed in value over the past century (see Figure 1). In the early 1900s there was no alternative for avoiding failure, and maintenance was considered a necessary evil. In the years 1950-2000 maintenance could be planned and controlled, because of techniques like preventive maintenance and condition monitoring. Nowadays maintenance creates additional value as an integral part of the business process (Parida and Kumar 2006).

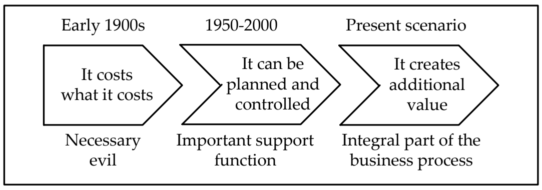

Figure 1: Paradigm shift in maintenance (adopted from Parida and Kumar 2006, p.240)

Maintenance is driven by defined objectives based on the requirements of different internal and external stakeholders that vary from production targets to safety regulations. Maintenance is triggered by planned repair or equipment failure and is a crucial process in keeping the equipment fit, safe to operate and well configured to perform its task. This process requires planning, scheduling, control and the deployment of maintenance resources to perform the necessary maintenance activities, and considers preventive and corrective maintenance (Duffuaa, Ben-Daya et al. 2001). In order to know if the determined objectives are reached or what actions have to be taken to improve the operations, maintenance performance has to be measured (Arts, Knapp et al. 1998).

Maintenance performance measurement can be supported by Enterprise Resource Planning (ERP) systems and many organizations have implemented an ERP system to streamline and integrate operation processes and information flows (Nikolopoulos, Metaxiotis et al. 2003).

ERP systems were introduced as the solution to improve the overall organizational operating efficiency and effectiveness of large complex business organizations, by integrating all the information flowing through an organization into a unified system, with several applications that are linked to one central database (Davenport 1998; Rashid, Hossain et al. 2002).

Problem description

As part of a global IT standardisation effort, this client has globally implemented the Enterprise Resource Planning (ERP) system of the software enterprise, SAP, to support their business processes. The researched asset has also implemented this system. Accenture, a global management consulting, technology services and outsourcing company, is supporting the client in the implementation and benefit realization of SAP.

The implementation of SAP enabled the possibility for the client to measure the real-time performance of its maintenance process and control this process based on this information. The client experienced problems with achieving the desired performance of some of the maintenance processes at their assets. The client experiences a large backlog of maintenance work orders and assumes this influences the performance in a negative way. Therefore the client wants to know how this backlog and the maintenance performance will develop in the future and which interventions can influence the backlog and performance in a positive way.

This paper presents the results of a research project in which System Dynamics Modelling is used to analyse performance improvement problems of a corrective maintenance process. This research focused on one production plant of the client where the activities of the maintenance process that are performed by the employees are stabilised after the implementation of SAP, but where the desired performance has not been reached and therefore the employees do not experience the promised benefits of SAP.

The client wants to use Group Model Building (GMB) (Richardson and Andersen 1995; Vennix 1996) to structure the problem of the maintenance performance achievement, together with the employees of this process. The client expects that these sessions will contribute to the increase of insight in the maintenance process, for management, but also for the employees who execute the process. In several GMB sessions the problem needs to be structured and visualised in order to convert this into a Dynamic Business Model, with which the dynamics of this problem can be simulated and the effect of possible interventions in the process can be evaluated.

The main question of this research is:

> *How to improve the performance of the Corrective Maintenance process of the client's asset by means of a Dynamic Business Model with which possible interventions can be evaluated?*

To answer this research question, first the maintenance process and terminology and secondly the methodologies that have been used to develop the Dynamic Business Model are described.

Purpose of this paper

The purpose of this paper is to present a case study of a maintenance performance improvement problem analysis with System Dynamics, with a reflection on the suitability of System Dynamics for these kind of problems. Therefore only the relevant parts and results of the research project, for this purpose, are presented in this paper.

First Maintenance is described as the subject of this research problem, after which the methodologies used (Group Model Building and System Dynamics) to structure and analyse the defined research problem are presented. Following this, the problem is structured in more detail by means of a system analysis, and the general structure of the model is explained. Next the validation process is discussed. Then the results of the different simulation runs are presented, after which the conclusions and recommendation for the client are formulated. This paper concludes with a reflection on the use of System Dynamics for analysing maintenance problems and recommendations for further research. For confidentiality reasons, the model diagrams and equations are not presented, instead the more general model formulation diagrams are presented in the appendix as well as an overview diagram of the model.

Maintenance

Maintenance is defined in the European standard of Maintenance Terminology as:
"the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function."(CEN 2001, p.8)

The standard maintenance workflow is presented in Figure 2 and defined as a
"set of sequenced steps to be followed, in order to accomplish a maintenance operation, from the first preparatory activities, such as study and defining policies, to the analysis once the work is finished and action to be taken to improve future similar cases" (CEN 2002, p.5)

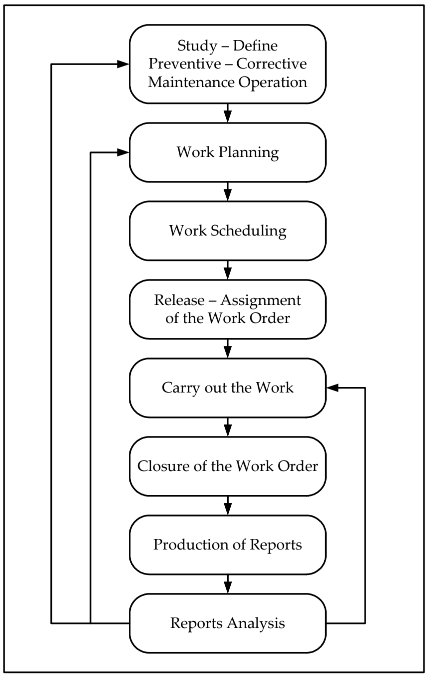

Figure 2: Maintenance workflow (Adopted from CEN 2002, p.22)

According to Duffuaa et al. (2001), the input to this maintenance process is the generated maintenance load by production and operational processes. This maintenance load is converted into work orders that are planned, scheduled and executed (Duffuaa, Ben-Daya et al. 2001).

A work order is a
"document containing all the information related to a maintenance operation and the reference links to other documents necessary to carry out the maintenance work" (CEN 2002, p.6)

The execution of these work orders is performed according to prescribed maintenance procedures with utilization of necessary maintenance resources, like manpower, materials, spare parts, tools, equipment, standards and procedures. These maintenance activities are accomplished by interactions with maintenance support functions, such as operations, materials and inventory control, and engineering and technical support. The maintenance is controlled and the process is improved based on the generated reports and performance measurements (Duffuaa, Ben-Daya et al. 2001).

Preventive and Corrective Maintenance

Different types of maintenance can be defined. Figure 3 shows the classification of these different types of maintenance.

Preventive maintenance can be scheduled according to a predetermined time schedule (Predetermined maintenance) or scheduled based on a condition, based on monitoring of parameters and/or performance and further actions (Condition based maintenance) (CEN 2001)

Corrective maintenance can be performed without a delay after the fault has been detected (Immediate maintenance) or with a delay according

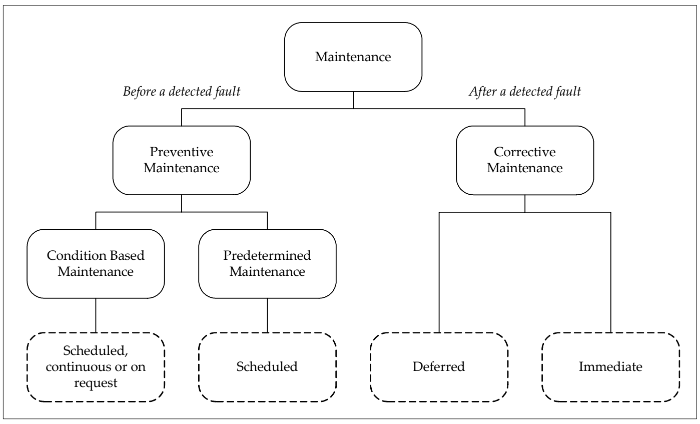

Figure 3: Maintenance terminology (adopted from CEN 2001, p.36)

with given maintenance rules (Deferred maintenance) (CEN 2001).

The total maintenance workload always consists of preventive and corrective maintenance. The organization's policy in combination with the plant's state determines the division between these two types of maintenance. Maintenance jobs are preventive or corrective, dependent on whether the maintenance job has arisen before or after a fault. Preventive maintenance is determined based on the time the, parts of the, installation have been operational and is scheduled up front. Corrective maintenance jobs arise from faults and are assigned a certain priority by the originator of the work request. This priority determines the sequence of work planning, the highest priority jobs are first in line to be planned and scheduled. High priority corrective orders are scheduled before low priority preventive orders. The priority is based on the criticality of the equipment and on the type of work that has to be performed and can be determined with an organisation specific ranking index or risk matrix.

Methodologies

The Dynamic Business Model has been developed using the problem structuring method *Group Model Building* (GMB) (Vennix 1996) which is a problem structuring method in which the end-users are involved throughout the process of model building. This involvement has a two-way effect, namely insight of the model builders in the problems and needs of the end-users and trust and understanding from the end-users in the model (Vennix 1996). GMB will be used to build the Dynamic Business Model together with the employees of client's asset. The methodology of GMB is suitable for this research because it can also influence the user attitude towards the Corrective Maintenance process and the ERP system which supports this process.

The methodology used to formulate the Dynamic Business Model is *System Dynamics* (SD). The research problem is complex and dynamic due to the interrelations, the feed-back loops and time delays in the Corrective Maintenance process which is supported by SAP.

Baines and Harrison (1999) describe that computer simulation of manufacturing systems, like maintenance, was commonly carried out using discrete event simulation (DES) and that there is a lack of exploitation of System Dynamics within manufacturing. They address that System Dynamics is more suited to modelling systems at an aggregate level of detail and conclude that manufacturing system modelling does represent a missed opportunity for System Dynamics modelling, especially in the higher levels of decision making (Baines and Harrison 1999).

System Dynamics was selected as a modelling methodology for this research and used to build a Dynamic Business Model with which the Corrective Maintenance process of the client's asset can be simulated, because it is closely related to Group Model Building and a logical continuation of GMB sessions and it is assumed to be suitable for modelling the Corrective Maintenance process. Therefore in the model validation, the suitability of System Dynamics for the modelling of maintenance processes needs to be evaluated.

The Group Model Building process

The GMB process is visualised in Figure 4 and was performed with 12 participants who were selected together with the client.

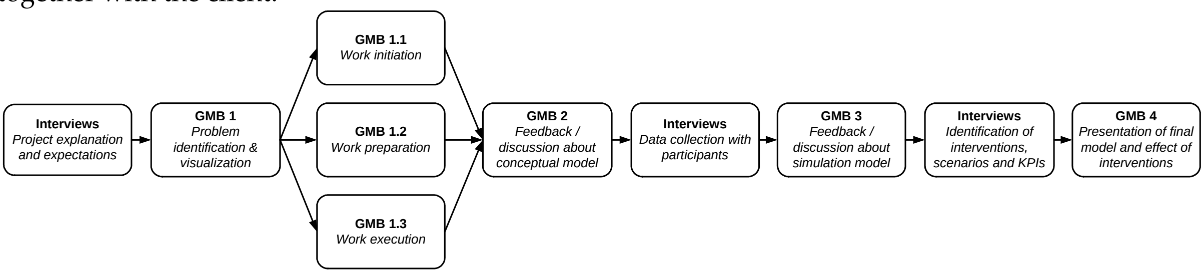

Figure 4: Group Model Building process

These participants are all employees involved in the Maintenance process of the client's asset and cover every aspect of the process.

Demarcations
In the first GMB session the scope of the System Dynamics Model was defined together with the participants. The demarcations defined during the GMB sessions are:

- The orders in the Corrective Maintenance process can vary in seven priorities, which determine the urgency of the corrective maintenance. Therefore the orders are modelled in seven different types in one process;
- The participants wanted to analyse the Corrective Maintenance process in detail for all priorities, instead of also analysing the Preventive Maintenance process. Therefore only the Corrective Maintenance process is under study, so not the Preventive Maintenance process which is executed by the same employees;
- The origination process of the maintenance workload is not taken into account, but is used as an inflow to feed the model;
- The work completion step is not taken into account, because this step only considers administrative tasks and does not affect the physical Corrective Maintenance process;
- The process of purchasing materials is outside the boundaries of this research, due to the fact that it is not performed by the client's local employees and because there is a lack of data of this process step. Therefore this process step is considered as a black box and a SAP cycle time is used to model this step.

The Corrective Maintenance process
The client's definition of Corrective Maintenance is:

> *"Any maintenance activity which is required to correct a failure, that has occurred or is in the process of occurring. This activity may consist of repair, restoration or replacement of components."*

Corrective maintenance issues, according to this definition, can be identified and reported in a notification by any employee involved in the process. These notifications are reviewed by some key employees in the notification review meeting and can be approved so theses notifications are in progress. The work preparation employees take the notification in progress to create work orders and prepare these work orders with a work package after which they can be approved and released. If materials are needed to be purchased this is performed by the purchase employees and the work orders are scheduled for execution if the materials are in stock. The work execution employees (called base crew) execute the work orders and when all the operational steps are executed the work order is confirmed. The different process steps that were analysed are presented in Figure 5.

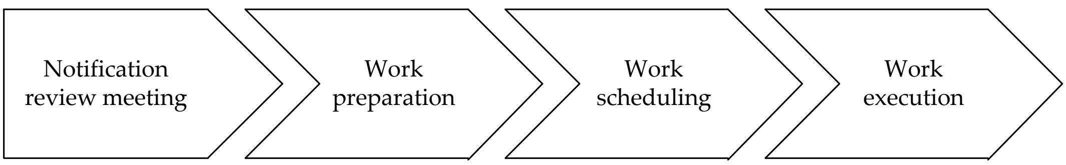

Figure 5: Corrective Maintenance process steps[1]

Together with the GMB-participants a stock and flow model was developed, in which the identified variables and their relations were visualised. This model building was performed in general sessions and in smaller sessions with the employees of the relevant process step.

This stock and flow model was specified with data from estimations of the participants and SAP data analyses, and converted into a simulation model. (The formulation of this simulation model

[1] The work preparation process step is actually called work planning (making a work plan). Work preparation is selected as the term used, to prevent misunderstandings in the Group Model Building process, because the Dutch word planning means scheduling.

is presented in the appendix.) These steps in the process of model building are discussed in more detail in the next section, which concerns the validation of the simulation model.
Interviews were held with the participants to identify the performance indicators, realistic interventions and external factors that influence the corrective maintenance process. Finally the current situation is simulated, as a base case, for the next three years and evaluated based on these performance indicators. Also four interventions and two external factors were selected and simulated for the next three years. The effects of these interventions and external factors are evaluated on the performance indicators and compared to the base case. The results were presented to the participants in the final presentation.

System analysis of the Corrective Maintenance process
A system analysis is used to demarcate the process under study, interventions that can be influenced by the client, external factors that cannot be influenced by the client and performance indicators that are used to measure the system performance. This analysis is presented in the system diagram of Figure 6 and is described in this section.

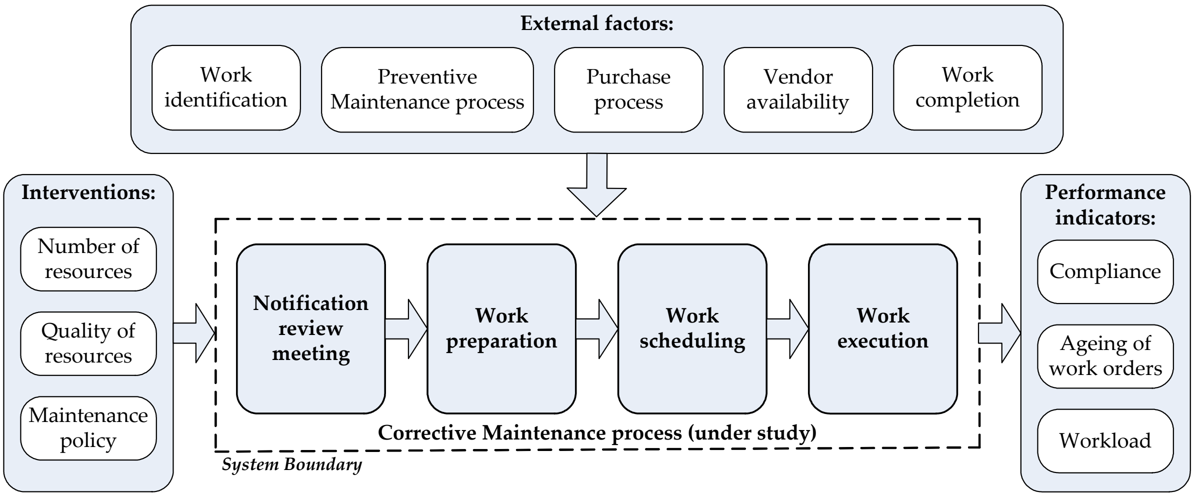

Figure 6: System diagram of the Corrective Maintenance process under study

The Corrective Maintenance process steps that are formulated in the model, the notification review meeting, work preparation, work scheduling and work execution, are presented within the system boundaries. The factors outside the system boundaries are divided into three categories:

- *Performance indicators* that are used to measure the Corrective Maintenance performance, caused by the system behaviour;
- *Interventions* that the client can execute to change the system behaviour;
- *External factors* that cannot be (directly) influenced by the client.

Performance indicators
The client has defined Key Performance Indicators (KPI) that measure the maintenance performance. In interviews with the participants of the Group Model Building sessions the important KPIs for the Corrective Maintenance process were identified. These KPIs are formulated in the model and are used to evaluate the effects of the different simulation runs.

Compliance
The main KPI is maintenance *compliance* which monitors whether the Corrective Maintenance (CM) work has been completed within the time window set by the priority. Compliance measures the processes work preparation, scheduling and execution. In the model a *compliance indicator* is formulated that divides the time window, set by the priority, by the calculated average total CM-process ageing-time per priority. This compliance indicator is not the same as the compliance

measured by the client, as it is not possible to look at individual entities in a SD model, but it can be used for the evaluation of the simulation runs as a total process KPI.

Ageing-times

While the compliance indicator is based on the sum of all ageing-times, these ageing-times of the single process steps gain insight in the more precise location of the performance realisation problem. The ageing-times indicate the average time an order is in that particular process step. Also the proportions of the specific ageing-times compared to the total process ageing-time are determined. This enables determining the contribution of a specific process step to the entire process performance.

Workload

The KPIs discussed above concerned indications of the progress of the Corrective Maintenance (CM) process. Other KPIs are defined that concern the quantity of the CM-process: the workload.
These workload KPIs are defined for the total number of orders in the different process steps, but also divided by the number of employees involved. This enables benchmarking of the client's asset with other assets of a different size. These KPIs are an indication of the workload of the different process steps, and especially the changes of these workloads over time indicate the effect of the allocated resources and their capacity. Two other KPIs are added to the model to indicate if all the work preparation (WP) and execution (base crew; BC) capacity is used; WP and BC over capacity. These indicators are helpful when determining the desired resource allocation of the model.

Interventions and external factors

For the analysis of the Corrective Maintenance process not only interventions are identified that the client can perform to change the process behaviour, but also external factors, that cannot be influenced by the client, are identified to gain insight in the effects of changes in these factors. The related parameter values are changed in different simulation runs in order to evaluate if these changes have a significant effect on the performance. If the performance can be significantly increased by the change of these parameters it is recommended to further investigate the possibilities to change these factors in reality.

The selected interventions are:

- *Improve the quality of the documentation,* which changes the quality of the resource documentation and decreases the amount of rework, which increases the WP capacity available for CM.
- *Change the number of Work preparation employees*, which changes the WP capacity;
- *Change the number of Base crew employees*, which changes the BC capacity;
- *Decrease the percentage of ineffective time in Work execution*, which changes the efficiency of the maintenance crew. If the effects of this intervention are positive, further research should indicate in which way this decrease can be realised, for instance, with a better schedule, or a maintenance crew that works better according to schedule.

The selected external factors, which cannot be influenced directly by the client, are:

- *Work identification*: the inflow in the notification review meeting is selected to gain insight in the effects of a decrease or increase in the inflow of notifications on the KPIs;
- *Purchase process:* the purchase time is selected to gain insight in the effects of a decrease of the purchase time on the KPIs.

Validation
For the validation process the simplified version of the modelling process of Sargent (1998) is used. This modelling process is presented in Figure 7 and the different steps are described in this section.

Conceptual model validation
The Group Model Building sessions were used to transform the problem entity (the Corrective Maintenance process) into a conceptual model (stock and flow model) in which all the identified relations and variables are visualized. Because in the sessions the participants agreed on the final stock and flow model, this model was face validated by the participants.

Data validation
The data that has been used originated from the GMB sessions with the participants and from SAP data analysis. Because the Corrective Maintenance process is administrated in SAP, a lot of data was available. This data availability made it possible to first validate the individual formulated sub models, before validating the entire model. Parameters concerning the individual sub models could be estimated on different data than data that was used to match the historical behaviour. Therefore the model building was not extremely dependent on the parameter estimation capabilities of the participants. In practice this was an iterative process between the estimations by participants, analysis of the SAP data and checking the parameters with the modelled behaviour.

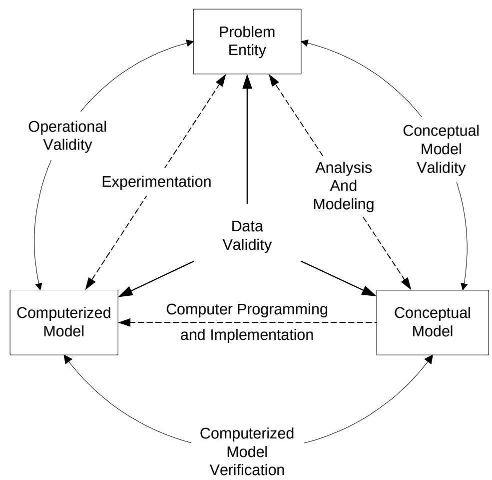

Figure 7: Simplified version of modelling process (adopted from Sargent, 1998)

Computerised model verification
The stock and flow model was implemented in a computer model with the software Dynaplan Smia (www.dynaplan.com). To test whether the computer programming and implementation of the stock and flow model is correct, computerised model verification was performed (Sargent, 1999). Three important tests were executed to verify if the stock and flow model is correctly implemented:
- The *dimensional consistency test* has the purpose to verify whether each equation is dimensionally consistent without the use of parameters having no real world meaning (Sterman 2000);
- The *extreme condition test* is performed to verify whether the model is robust in extreme conditions. The purpose of this test is to verify if each equation makes sense, even when its inputs take on extreme values (Sterman 2000);
- The *numerical integration sensitivity test* has the purpose to verify if the model results are insensitive to the choice of the time step or numerical integration method (Sterman 2000).

Based on the results of these tests it can be concluded that the stock and flow model has been implemented correctly in the simulation software.

Operational validation
The verified computer model must also be validated to investigate if it is suitable for the defined objective. This can be performed by several operational validation tests (Sargent, 1998). Three of these tests were selected to test the operational validity of the System Dynamics Model:
- The *fixed value test* is used because the model inflow is capricious. This capriciousness can make it hard to understand the model behaviour. A test that allows checking model results against easily calculated values is the use of fixed values.
- *Sensitivity analysis* is used because for the formulation of the model, assumptions are made about relations and parameters are estimated. A sensitivity analysis has the objective to validate these

assumptions and estimations for uncertainties. All parameters have to be tested and if a small deviation of the parameter value causes a relative greater deviation on the model behaviour, the parameter is sensitive (Sterman 2000). The sensitivity analysis was also used to identify possible policy parameters for interventions in the process. Parameters that can be changed in reality, like the number of employees, and cause a significant change in the model behaviour can be used to define possible interventions.

- The final test of the operational validity was the *historical data validation*. The equations that were formulated and the parameters that were estimated on the period 01-08-2006 – 28-01-2007 are tested whether these can reproduce the historical data of the system statuses (of the corresponding process step) in the period 29-01-2007 – 31-07-2007. For this test the same objectives are used as for the parameter estimation on the first period of historical data. These objectives are that the model behaviour should *follow the trend* of the historical data and the behaviour should *approximate the numerical values* of the historical data, in other words: the number of orders should be approximately the same.

The operational model validation has indicated that the model behaviour is realistic and not sensitive to small changes of the parameter values. Also the trends and numerical values can, besides certain identified incidents, be reproduced by the model. Only priority 1 and 2 could not be reproduced due to the small number of orders with these priorities.

Applicability and suitability

The emphasis in the model building was on the modelling of the work preparation and execution phases. The purchase process was beyond the scope of this research and therefore the model can be identified as unbalanced, because the work preparation is formulated in much more detail than the rest of the model, with much less detail in the formulation of the purchase and schedule department. Therefore no interventions in the purchase or schedule process can be formulated in the model, but the change of certain external factors will be evaluated instead.

The model is suitable for the analysis of priority 3-7 and proper interventions can be identified for the work preparation and execution department. Considering the purchase and schedule department, only the influences of a shorter cycle time can be analyzed, but not the factors that determine this cycle time.

The model can not be applied for the analysis of the Preventive and Corrective Maintenance proportion, because only the effects on the execution of Corrective Maintenance orders are considered in the model.

If the previous mentioned remarks are taken into account, the model can be applied for further analysis.

Results

The validated model is used to analyse the Corrective Maintenance process. The current situation is simulated, as a base case, for the next three years and evaluated based on the defined performance indicators. Also the identified interventions and external factors were simulated for the next three years. The effects of these interventions and external factors are evaluated on the performance indicators and compared to the base case. This section presents the results of the performed simulation runs. The effects of the base case simulation run and one intervention are described in detail and an overview of the effects of the remaining interventions and external factors are presented in a table.

Because the Asset Manager is interested in structural, long term improvements the simulations are run for the period of 3 years, starting at August 1, 2007. The model is therefore initialised with the SAP data of August 1, 2007. A fixed inflow is applied, because for long term behaviour capriciousness is not relevant and a fixed value analysis has shown that the model behaviour is not significantly different for the original and fixed value inflow. For the analysis of the behaviour of the Corrective

Maintenance process only the KPIs considering priority 6 are considered, because the trend of the behaviour is similar for priority 3-7 for each KPI. Although the numerical values of the KPIs differ, this only affects the compliance indicators, because this affects whether the desired compliance is reached, and therefore this will be discussed in more detail.

<u>Base case simulation run</u>
This simulation run is executed to evaluate what will happen in the next three years without intervening in the process. This evaluation is performed on the defined performance indicators for the situation that all the assumptions made do not change.

Workload
The effects on the workload KPIs are presented in Figure 8 and indicate that the workload in the notification review meeting (NRM) is constant over time. This constant behaviour is caused by the fixed inflow and by the fact that the NRM-rework delay is modelled as a constant average.
The backlog of the workload of work preparation and work execution decreases to approximately zero in the next three years.
The workload of the purchase and schedule process step fluctuates around a constant value over time. This behaviour is caused by the average constant cycle time that is used to simulate this process step and the fluctuating preliminary behaviour of the work preparation workload.

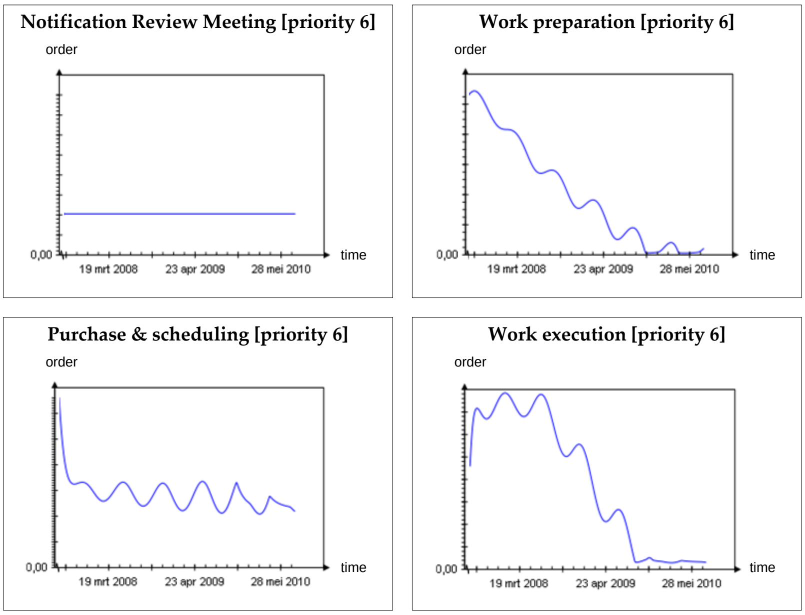

Figure 8: Workload of the different process steps

Key factors that influence the performance
Insight into the most important factors that influence the performance of the Corrective Maintenance process is gained from the compliance contribution graphs of the base case simulation run presented in Figure 9. These graphs indicate the contribution of the average ageing-time of the related process step to the compliance. These graphs indicate the current and future relative time consumption of the different process steps and do not consider the quality contribution. For instance, these

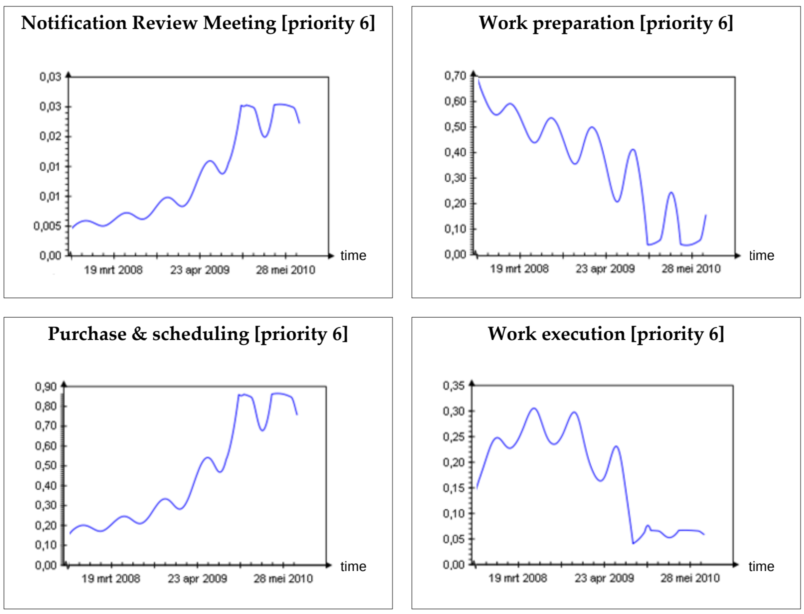

Figure 9: Compliance contributions of the different process steps

graphs show that the notification review meeting has a very small contribution (in ageing-time) to the compliance (3%) and that this increases over time, although the average ageing-time of orders in the notification review meeting is constant. This is caused by a decrease of the ageing-time in other process steps.

The *Notification Review Meeting* has a large contribution to the compliance, however if the quality in this process step is very low, then the probability is higher that orders with an incorrect priority scope are approved and that the description of the notifications is of bad quality, which makes is difficult to plan and schedule the order correctly. If the notification review meeting is not present in the process, the participants assume that there will be much more rework, and the specific task will take longer because the notification is incorrectly described. But this process step at the client's asset has already improved the process.

Work preparation has the largest contribution at the beginning of the simulation period (70%), but this decreases eventually to approximately 10% by a decrease of the ageing-time in work preparation that is caused by the decrease of the workload in this process step.

The purchase and schedule process increase in contribution from 15% to approximately 85%, although this process step is modelled by a constant average cycle time. This is caused by the decrease of the ageing-time of other process steps, which results in relatively smaller ageing-times for these process steps in comparison to the ageing-time in this process step.

Work execution increases in contribution on the short term from 15% to approximately 30%, but on the long term it decreases to approximately 5%. This short increase is caused by the decrease of the workload in work preparation, which causes an increase in inflow of work execution. To explain this behaviour the relationship is visualised in Figure 10.

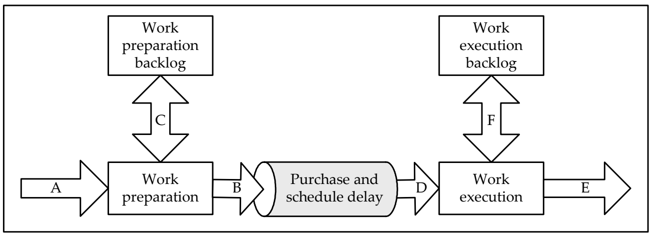

Figure 10: Relation between key factors

The definitions of the arrows are:

A. This arrow represents the regular inflow into the Corrective Maintenance process;
B. The outflow of Work preparation (WP) represents the prepared work orders. This outflow is driven by the capacity of the WP labour force;
C. This arrow represents the backlog transfers. If A > B then C represents the inflow of orders into the backlog, because the WP capacity is insufficient to prepare the regular inflow into the Corrective Maintenance process. If A < B then C represents the outflow of orders from the backlog. These orders are prepared and flow out of Work preparation;
D. This arrow represents the number of purchased and scheduled work orders and is driven by the average constant cycle time in the model. In reality not all orders need materials and not all materials need to be purchased, but can also be on stock. Orders are scheduled if the materials are present, based on the base crew capacity;
E. This arrow represents the executed work orders and is driven by the capacity of the base crew;
F. This arrow represents the backlog transfers. If D > E then F represents the inflow of orders in the backlog, because the Base crew (BC) capacity is insufficient to execute the purchased and scheduled orders. If D < E then F represents the outflow of orders from the backlog. These orders are executed and flow out of Work execution. In reality work orders are scheduled based on the available BC capacity, which will move the backlog from Work execution to Work scheduling.

The relative differences between the regular inflow in the Corrective Maintenance process, WP and BC capacity determine the location of the bottleneck.

This figure shows that the behaviour of the Corrective Maintenance process is similar to supply-chain behaviour. Bottlenecks in an early stage of the supply chain determine the flow in the remaining part of the supply chain. Therefore if the client wants to improve the Corrective Maintenance process, first bottlenecks considering early stages, like work preparation, need to be resolved, before other bottlenecks can be resolved. It is important to adjust the WP and BC capacity to the inflow of the process, and to determine the extra capacity based on the time within which the backlog needs to be resolved.

Compliance indicators

The compliance measures the total process performance, and in the model an average value is calculated by dividing the time window, set by the priority, by the calculated total ageing-time of the CM-process. Because the model does not treat orders as single entities, but as average flows, the model results can not determine if the desired compliance is reached. The formulated compliance indicator does indicate that if this value is above 1, the average total ageing-time is smaller than the time window set by the priority. As shows in Figure 11 this value differs for each priority, which is caused by the different time windows of the priorities. These graphs show that if the client keeps working this way, and the external factors, like the number of originated notifications, do not change, a higher compliance is automatically realised, but this compliance is not sufficient (on average) for priority 3 and 4.

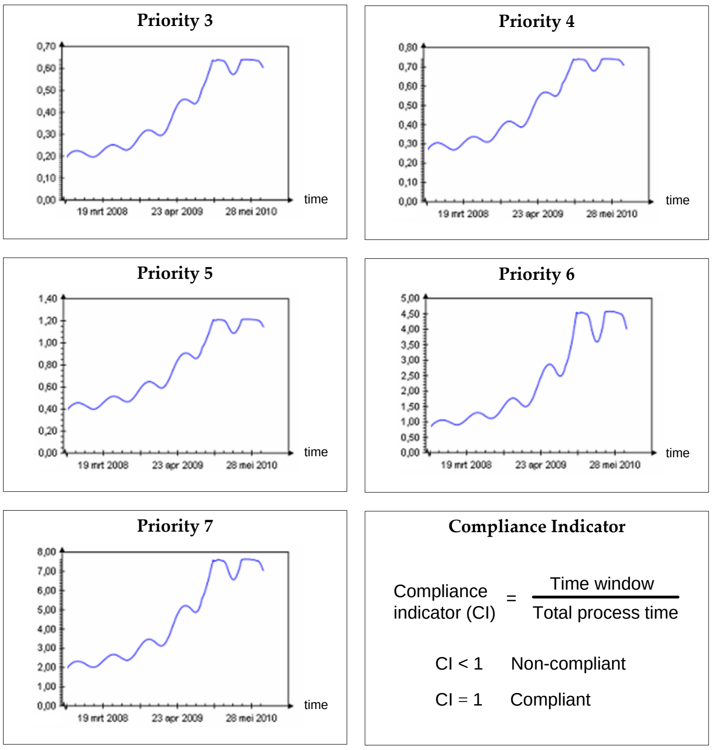

Figure 11: Compliance indicators for priority 3 to 7

Decrease the percentage of ineffective time an order is in execution

As previously mentioned the model results have indicated that the behaviour of priorities 3-7 shows a similar trend. Therefore the interventions are evaluated on a single priority (priority 6). The interventions are evaluated in the base case scenario. So assuming the inflow of notifications does not change over the next three years. The results of the base case scenario are represented by the green line (0% decrease); which represents no intervention. The intervention is evaluated in two strengths; a decrease of 10% (the red line) and a decrease of 20% (the blue line) in the ineffective time and the relevant results are presented in Figure 12 and described in this section.

An analysis of the actual hours of the base crew has indicated that the time an order is in execution is only determined by the execution process of the base crew for a small fraction. The remaining time the order is handled by vendors, reworked or waiting for execution. The assumption is that the percentage ineffective time in the work execution process step can be decreased by a more effective schedule. This simulation run only concerns the effect of a decrease in inefficient time. If and how this can be realised should be further researched if this decrease has sufficient impact on the performance.

The behaviour of the workload in work execution indicates that this intervention has a large impact. Because the ineffective time between the different operational steps is decreased the work orders are executed much faster, which causes an early base crew overcapacity.

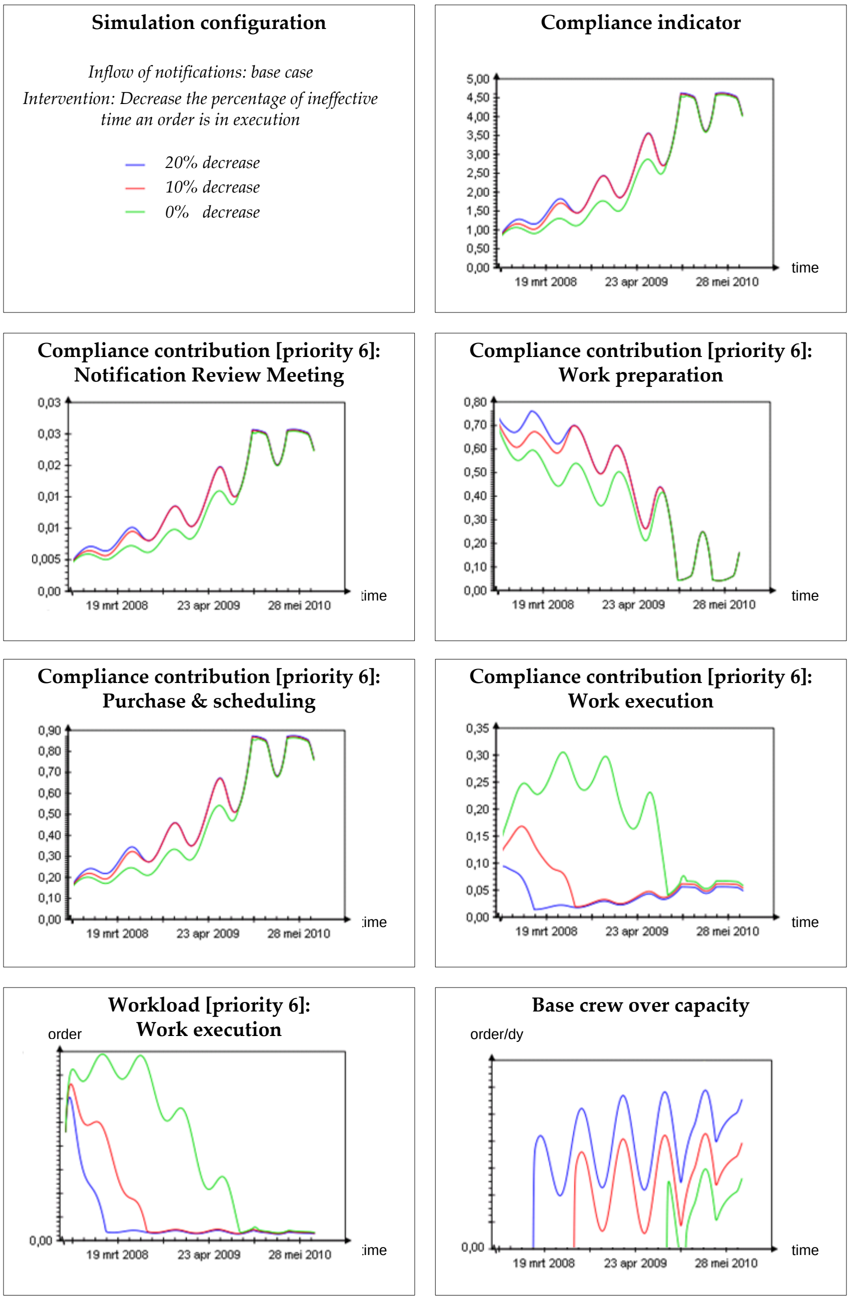

Figure 12: Decrease the percentage of ineffective time an order is in execution for base case scenario

The result of a decrease of the ineffective time an order is in execution on the compliance indicator is positive for the short term, but on the long term the same compliance indicator is reached for all percentile decreases of the ineffective time, because for each simulated value of the inflow of notifications the work execution workload is decreased to a similar amount of orders that is reworked. Therefore it can be concluded that this can be a short term intervention in realising a fast decrease of the base crew workload in work execution.

Because the decrease of ineffective time in work execution does not concern the hiring of extra employees, and if the assumption is right that this decrease can be realised by a more effective schedule, this can be a cost-efficient and performance effective intervention. Therefore it is recommended to further investigate the possibilities of realising this decrease in ineffective time an order is in execution.

Overview of all simulation runs

Table 1 presents an overview of the simulated changes in external factors and interventions for different values of the inflow of notifications on the compliance indicator in comparison to the reference run. If the percentage in this table is smaller than 100%, the simulation run has a lower average compliance than the reference run. If the percentage is higher than 100% the average compliance of the simulation run is better compared to the reference run. The short term results represent the performance after one year and the long term results represent the performance after three years. The conclusions of the analysis are formulated according to the analysed process steps.

Compliance indicator in comparison to the reference run							
		inflow of notifications					
External factors		base run		increasing [+5%/yr]		decreasing [-5%/yr]	
Parameter	Change	short term	long term	short term	long term	short term	long term
Inflow of notifications	+ 5%/yr			-	-	-	-
	- 5%/yr			-	-	-	-
Purchase time	decrease with 20%						
Interventions							
Work preparation employees	- 1 person						
	+ 1 person						
Quality of documentation	increase to 100%						
Ineffective time in work execution	decrease with 20%						
Base crew employees	- 1 person						
	+ 1 person						
Work preparation employees	+ 1 person						
Base crew employees	+ 1 person						

Legend:

< 75%

> 75%
< 125%

> 125%

Table 1: Overview of the effects of the performed simulation runs

Conclusions and recommendations for the client

The conclusions and recommendations of the analysis are formulated according to the analysed process steps.

Work identification

An increase of the inflow of notifications has a very negative result on the compliance on the long term. The work preparation and execution capacity are not sufficient to resolve the inflow and the backlog within three years.

A decrease of the inflow of notifications has a small positive result on the compliance. Work preparation and base crew (execution) overcapacity is realised faster due to the smaller inflow of notifications, which causes more available capacity to resolve the backlog.

Work preparation

A decrease of the labour force with one employee has a negative effect on the compliance, therefore it is recommended not to decrease the work preparation labour force.

An increase of the labour force with one employee contributes to a higher compliance which is reached sooner. This is caused by a faster decrease of the workload in work preparation. This causes a higher outflow of orders from work preparation which results in a higher inflow of orders in work execution. This inflow is higher than the current base crew (execution) capacity which causes an increase of the workload in work execution, but when the workload in work preparation is resolved, this workload is also decreasing. An increase of the work preparation labour force can be recommended if the client want to reach the compliance faster in comparison to the reference run, but this intervention is not optimal because a bottleneck is indicated for the current base crew (execution) capacity.

An increase of the quality of documentation causes a very small positive impact on the compliance, but can be recommended because it not only increases the work preparation capacity available for the regular orders, but it also decreases the disturbances of the work preparation labour force, caused by rework.

Purchase process

The impact of a decreased purchase time on the compliance is small, but the analysis has indicated that the compliance will eventually be determined to a large extent by the ageing-time of the orders in the purchase and scheduling process step. The purchase process determines this ageing-time for approximately 80%. If the purchase time is similar to or larger than the time window set by the priority of the order it will be hard to reach the compliance. The compliance indicators of the different priorities have indicated that reaching the compliance is, on average, impossible for priority 3 and 4. Priority 5 will reach it in the long term and priority 6 and 7 will reach it in the short term. Because there is a lack of insight in the purchase process, an average constant value has been used for the purchase time. Not all orders need materials, and not all materials need to be purchased, therefore no conclusions can be drawn based on the difference between the time window and the used average purchase time, but additional research is recommended to increase the insight in this purchase process. For instance, more materials can be kept on stock, especially for the orders with a time window close to or smaller than the contractual agreed purchase time.

Work scheduling

The impact on the compliance of a decrease of 20% in the ineffective time an order is in execution is positive on the short term, because the workload in work execution is decreased faster. Because the decrease of ineffective time an order is in execution does not concern the hiring of extra employees, and if the assumption is right that this decrease can be realised by a more effective schedule, this can be a cost-efficient and performance effective intervention. Therefore it is recommended to further investigate the possibilities of realising this decrease in ineffective time an order is in execution.

Work execution

A decrease of the labour force with one employee has a negative effect on the compliance, therefore it is recommended not to decrease the base crew (execution) labour force.

An increase of the labour force with one employee contributes to a higher compliance which is reached sooner. This is caused by a faster decrease of the workload in work execution. Therefore this intervention can be recommended if the client wants to reach the compliance faster in comparison to the reference run, but this intervention is not optimal because a bottleneck is indicated for the current work preparation capacity.

Capacity bottlenecks

The interventions of increasing the work preparation or base crew (execution) labour force can be recommended, but both interventions have indicated that a capacity bottleneck occurs on the short term for the other capacity. The simulation run in which both interventions are performed has indicated that these bottlenecks are resolved if both the work preparation and base crew labour force are increased. This results in a higher compliance which is reached sooner. Therefore it can be recommended to increase both labour forces with one employee. The counterpart of these interventions is that work preparation and base crew overcapacity is indicated earlier if the related labour force is increased. Therefore the client should assess the possibilities of hiring temporary employees and allocating the permanent employees to other processes after the workload is resolved.

Compliance and safety
The compliance is measured to determine the percentage of orders that is resolved within the set time window determined by the priority. The priorities are defined based on a risk assessment matrix that takes into account the requirements of the different stakeholders. Therefore one could say that if the compliance is not reached the installations are unsafe. This is not entirely true, because the client has labelled the safety-critical orders. Based on these labels the client ensures that these orders are resolved to keep the installation safe. Therefore it is desirable to reach the target compliance, but the time within this is reached is more like a trade-off on the total cost level.

There are also certain recommendations concerning the extension of the model and generalisation of the research.

Model extension
The model should be extended in some aspects in order to provide more knowledge of the dynamics of maintenance at the client's asset. This extension is visualised in Figure 13 concerns the following aspects:

- Incorporation of the purchase process in the Corrective Maintenance model will increase the insight in this process and also interventions concerning this specific process are possible in the model. The current research has indicated that the Corrective Maintenance process is highly dependent on the purchase time, and therefore these insights are important for the Asset manager is the development of new policies.
- Incorporation of the Origination of notifications and the Preventive Maintenance process. This enhances the possibility to analyse the dynamics between these processes and the evaluation of the best preventive maintenance / corrective maintenance proportion.
- The incorporation of a financial model will give the evaluation of the interventions more meaning. Because the highest level of performance measurement is the level of total costs, interventions in the model should also concern this level of performance measurement. In reality, the general driver behind maintenance improvement is the cost aspect and therefore the interventions should also be evaluated on this aspect.

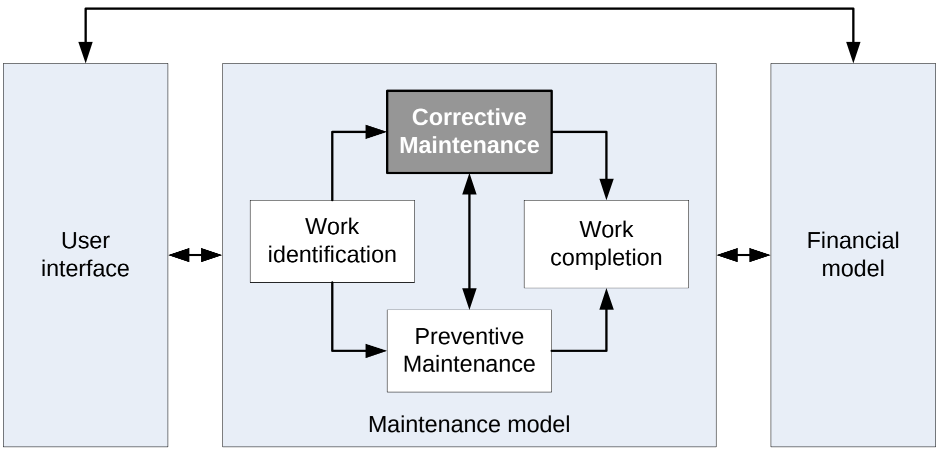

Figure 13: Model extension

Generalisation

The possibilities to generalise the developed model, to other assets of the client's organisation, should be further investigated. The prescribed approach in the conclusion should be tested on another asset. If this model can be re-applied to other assets it is an interesting instrument to improve the performance of the Corrective Maintenance process across the entire organisation. If the model is also extended as proposed in the previous model extension section, it could be even more interesting, because the model then represents a greater part of the asset specific organisation, so more interventions are possible to evaluate, and these interventions can also be evaluated on the financial performance indicators.

Reflection on the use of System Dynamics

System Dynamics modelling can only be applied to maintenance processes of which the workload can be represented as continuous flows. Therefore the number of maintenance orders determines the applicability of System Dynamics.

Because the maintenance process is supported by SAP, a lot of detailed historical data concerning the process is available. The pitfall of a lot of detailed historical data in a Group Model Building process is that the desire is to properly match the modelled behaviour with the historical data, to ensure the confidence of the participants on the model, and therefore the adoption by these participants of the model results. But modelling the behaviour on a less detailed level could lead to similar results without such a detailed model.

Reflecting on the developed model indicates that the modelled behaviour can be assumed similar for priorities 3 to 7. This is caused by the fact that the maintenance process of the client has already been stabilised. If all the priorities have the same behaviour, it could be possible to not make a distinction between the priorities, but merge these into one process flow. This does harm the insights into the complexity of the Corrective Maintenance process, caused by this priority division, but does enhance possibilities to broaden the scope and also model the preventive maintenance process and the purchase process.

The primary objective of System Dynamics models is to learn about a complex system and therefore the variables are aggregated to a high level and the model should not be used to predict and to prescribe. Campbell (2000) has evaluated the use of System Dynamics in business process improvement. The results of this evaluation are that System Dynamics is only suitable for modelling those processes that are dynamic (change over time) and include feedback (Campbell 2000).

The scope of this research project was (partly) determined by the participants of the GMB sessions and the client, therefore the focus was to first model only the Corrective Maintenance process into depth to gain insight in the complexity caused by these 7 priorities. The demarcations made in the GMB session resulted in the absence of the decision feedback loops as defined in the maintenance theory, the dynamics between preventive and corrective maintenance and the purchase process in the model. The model is also not valid for priority 1 and 2, because these can be considered discrete flows.

Considering the previous remarks, I agree with Baines and Harrison (1999) that System Dynamics is more suitable for maintenance problems, when they are modelled on an a more aggregate level, and do not include discrete flows but do include the dynamics between different processes, like preventive and corrective maintenance, but also the purchase process. Although if the process was modelled on an aggregate level the client would probably have asked what the behaviour of the different priorities was like.

From the model validation can be concluded that the developed model is, to a certain extent, suitable for modelling this corrective maintenance process. But due to the absence of real dynamics and decision feedback loops in the model, and the small impact the identified feedback loops (rework) have on the model behaviour, Discrete Event simulation could have also been used.

The Group Model Building has certainly increased the insight in the Corrective Maintenance process by the participants, but this might have been realised with other facilitation and problem-solving techniques, although stocks, flows and causal relations are not hard to understand. The choice of the simulation method could also have been made during the GMB process when more insight in the problem had arisen.

Because of the previous mentioned reasons, I would recommend to, even in a GMB process, keep the choice of the simulation method open, until a better insight is gained into the problem entity. A further recommendation is to model the maintenance process on a more aggregate level and combine corrective and preventive maintenance together with the purchase and financial process. This will enable the possibility to not only measure performance on a process level but also on the level of total costs.

Recommendations for further research

To further evaluate the suitability of System Dynamics it would be recommended to formulate the developed model in a Discrete Event Simulation software package and compare the results with the developed System Dynamics model of this research. It should be possible to properly simulate the behaviour of priority 1 and 2 and the exact compliance, instead of an average value. This should provide insight in the capriciousness of the process and the effect of disturbances like the identified incidents on this exact compliance.

To further evaluate the possibility to generalise this approach and the developed model for maintenance process improvement problems, it is recommended to apply the used approach to another client of Accenture who has such a problem. Another concrete application of the used approach should enrich the theoretical reference of this research project and, if the results are similar, anchor these results better in the scientific field.

Acknowledgements

This research was part of a broader research project and therefore I would like to thank Tom Venderbosch, a former student of the faculty of Business Science of the Radboud University Nijmegen, for his contribution to this project. His focus was on the use of Group Model Building (GMB) in an ERP optimisation process and therefore he was responsible for the preparation and facilitation of the GMB process.

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Appendix: Model formulation of the Corrective Maintenance process under study

Process steps– administrated in SAP

The corrective maintenance process is administrated in the SAP Plant Maintenance (PM) module in standard system statuses, which can be assigned to notifications and work orders and correspond with the different steps in the process. These steps are visualised in Figure 14 and described in this section.

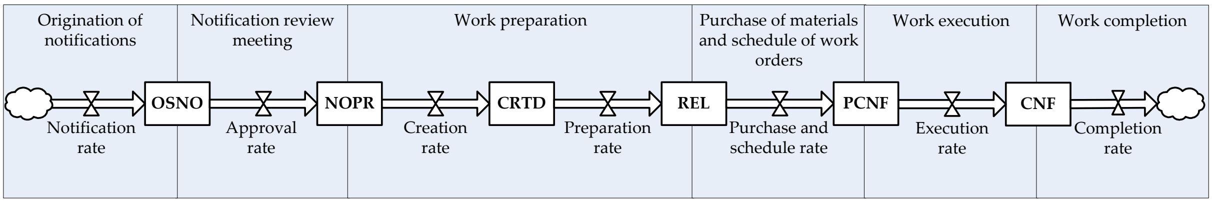

Figure 14: Mainstream of Corrective Maintenance process

- *Origination of notifications:* Corrective maintenance issues, according to the previous presented definition, can be identified and reported in a notification by any employee involved in the process. These notifications get the status outstanding notification (OSNO);
- *Notification review meeting:* the outstanding notifications (OSNO) are reviewed by some key actors and can be approved so theses notifications are in progress (NOPR);
- *Work preparation:* the work preparation employees take the notification in progress (NOPR) to create work orders (CRTD) and prepare these work orders with a work package after which they can be approved and released (REL);
- *Purchase of materials and scheduling of work orders:* the materials needed are purchased by the purchase employees and the work orders are scheduled for execution. The scheduling employees determine the time between the moment that the needed materials are expected to be present and the execution of the first operational step of the work order, when the work order is partly confirmed (PCNF);
- *Work execution:* The base crew employees execute the work orders and when all the operational steps are executed the work order is confirmed (CNF);
- *Work completion*: When the involved employees have allocated the hours and put the history into the system, the work order is technically and administratively complete.

The part of the process that is under study concerns the following steps:

- Notification review meeting;
- Work preparation;
- Work scheduling;
- Work execution.

These steps are formulated in several sub models that are described in the next section. A detailed description of the formulated model is presented in the supporting documents, but because the performed research is confidential the parameter values and equations are not included.

Notification review meeting

The notification review meeting is held every working day. During this meeting representatives of the CM-process review the outstanding notifications (OSNO) on detail of description and realistic priority. They can change the priority and if the notification has sufficient quality the notification is approved, if not the notification is returned to its originator to improve the description. These rework notifications wait for the next review meeting, the approved notifications pursue the regular CM-process. The possible priority change is not adopted in the model, because the used model inflow data has the final determined priority.

Some notifications with small maintenance issues bypass the regular CM-process. These issues can be solved with materials that are on stock and the issues are not that complex that they need to be prepared. These notifications leave the regular CM-process after they have the status NOPR (yearwork order rate) and are coupled to a yearwork order (YWO). These YWO are directly executed by the base crew. The structure of the notification review meeting sub model is visualized in Figure 15.

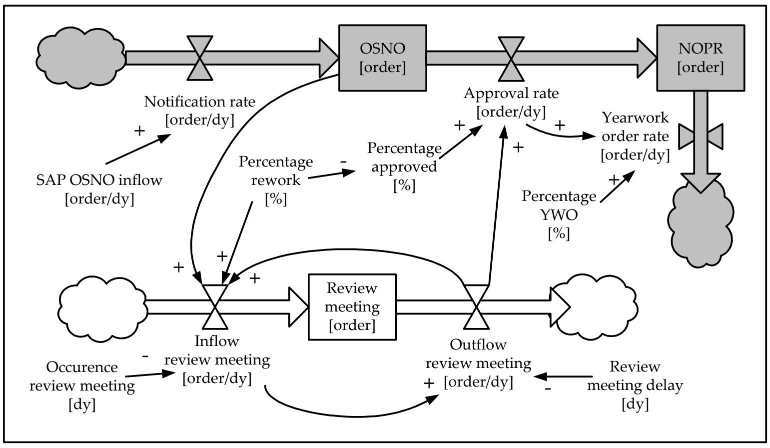

Figure 15: Notification review meeting sub model

Work preparation

The notifications in progress (NOPR) are picked up by the work preparation personnel, who create work orders (CRTD) of these notifications and prepare these with a maintenance plan, so they can be released (REL).

Sometimes notifications in NOPR don't have to be executed anymore, because there maintenance issue is already resolved with the execution of another order. These notifications are cancelled and leave the CM-process from the status NOPR (cancel rate).

Work preparation is formulated in several sub models. The work preparation capacity is determined by the labour force in the capacity generation sub model and allocated to the different priorities in the capacity allocation sub model.

Because the determined capacity is in reality used to create a work order and to prepare it, and this distinction could not properly modelled due to the time scale, the work preparation capacity only affects the creation rate. The initial orders in CRTD are added to the initial orders in NOPR and the preparation rate is equal to the creation rate.

Capacity allocation

The allocation of the work preparation capacity to the different priorities in NOPR is modelled in a structure adopted from the capacitated delay structure described by Sterman (2000). The structure used is presented in Figure 16. Capacity is claimed based on the number of orders in NOPR and the target preparation delay. Whether the claimed capacity is also the allocated capacity depends on the available capacity (Sterman 2000)

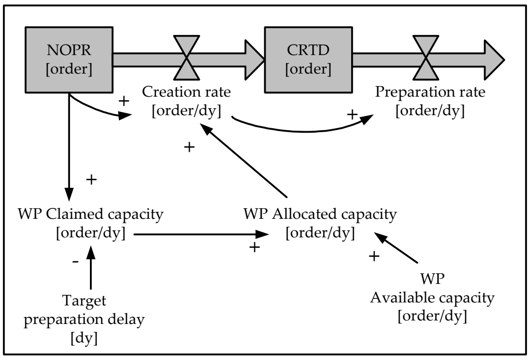

Figure 16: WP Capacity allocation sub model (adopted from Sterman 2000, p.554)

Because the claimed capacity has to be allocated to seven different priorities another structure is formulated that allocates the claimed capacity in the following order. First priority 1, then priority 2, then rework (which will be discussed after the description of the sub models of the regular process) and the remaining capacity is divided between priority 3 -7 based on their mutual proportion of the total number of orders in priority 3-7. This structure is formulated as an array function in the different variables and is presented in Figure 17. Because this formulation is the essential structure of the model it is explained in more detail.

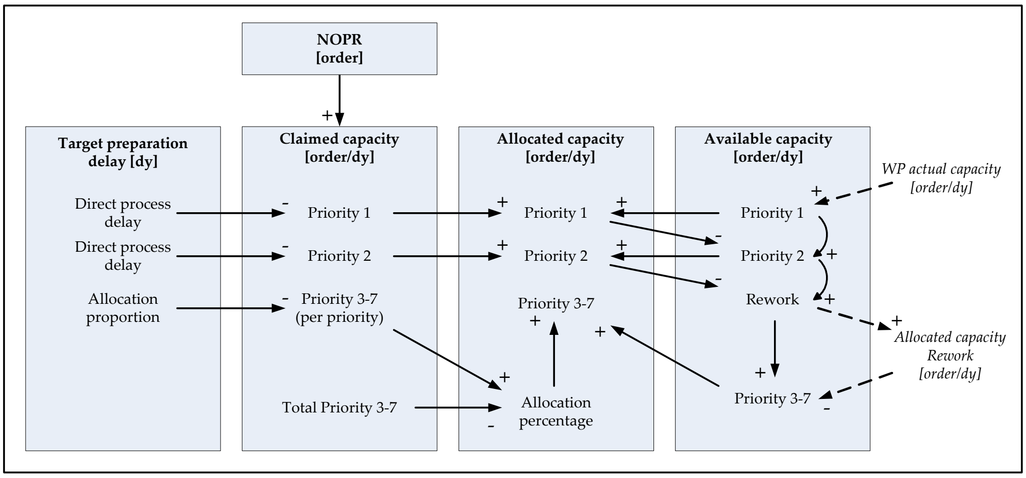

Figure 17: WP Capacity allocation sub model in detail

Priority 1 and 2

Priority 1 and 2 contain orders with maintenance jobs of a high urgency. Therefore these orders are prepared directly when they get the status NOPR.

The *claimed capacity* represents the capacity needed to prepare the number of orders in NOPR within the target preparation delay. The claimed capacity [order/dy] is determined by dividing the number of orders (of that priority) in NOPR [order] by the direct process delay [dy].

The *direct process delay* [dy] represents a delay of one day, which results in a claimed capacity for priority 1 and 2 that is needed to prepare the order in 1 day.

The *allocated capacity* [order/dy] is the minimum of the claimed and available capacity. The available capacity for priority 1 is the total capacity generated by the work preparation labour force. The available capacity for priority 2 is determined by the available capacity for priority 1 minus the allocated capacity of priority 1.

Rework

The available capacity for rework is determined in a similar way, but with the capacities of priority 2. The capacity allocation to the rework orders is described later on in this paper and only affects the available capacity for priority 3-7, which is determined by the available capacity for rework minus the allocated capacity for rework.

Priority 3-7

The available capacity for priority 3-7 is divided between these priorities.

The *allocation proportion* [dy] represents the target preparation delay of priority 3-7 in an array. The allocation proportion determines the claimed capacity which represents the capacity needed to prepare the number of orders in NOPR within the target preparation delay, for the individual priorities 3-7. But because the available capacity for priority 3-7 is not infinite, the percentages claimed capacity per priority of the total claimed capacity for priority 3-7 are calculated and multiplied by the available capacity for priority 3-7. This represents the structure that capacity is allocated based on the target preparation delay, but also based on the number of orders in NOPR. So if there is a relative increase in number of orders in NOPR for priority 7 in comparison to the orders of priority3-6, more capacity is allocated to priority 7.

Capacity generation

The *available capacity* for work preparation is generated by the work preparation labour force in the capacity generation sub model. The main structure of this sub model is presented in Figure 18.

The *labour force structure* is divided into three categories of employees (juniors, mediors and seniors) with a corresponding productivity fraction. The hiring, quitting and promotion structure of these employees is adopted from the two-level promotion chain from Sterman (2000). This is a simple and effective way to model the career curve for new employees (adopted from Sterman 2000, p.505-506).

The *experience structure* measures the average and total effective experience of the labour force by using a structure that is adopted from Sterman (2000). This structure tracks the experience of the labour force, by the increase in on-the-job experience and experience from hiring, and the decrease of experience due to decay and attrition (Sterman 2000, p.505-508).

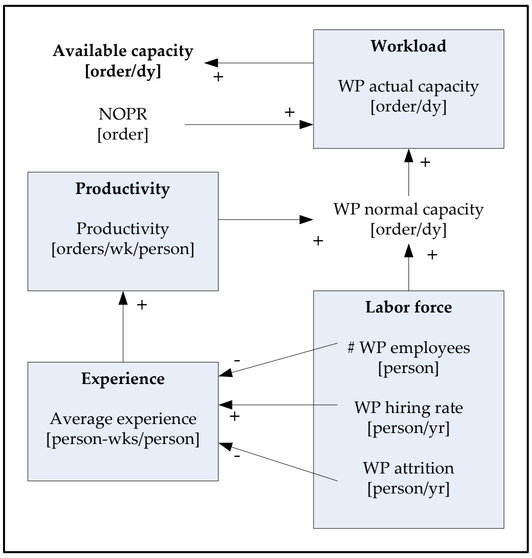

Figure 18: Main structure WP capacity generation

According to Sterman (2000), the *productivity* of the labor force is influenced by the average experience determined in the experience sub model (Sterman 2000, p.507). In the model this productivity is not only influenced by the experience, but also by the attendance of the work preparation employees needed for other processes. The experience increase causes a net increase, and the needed assistance for other processes causes a sinusoidal behaviour around this net increase. The determined base productivity is multiplied by the productivity fractions defined in the labor force sub model, to determine normal capacity of the labor force.

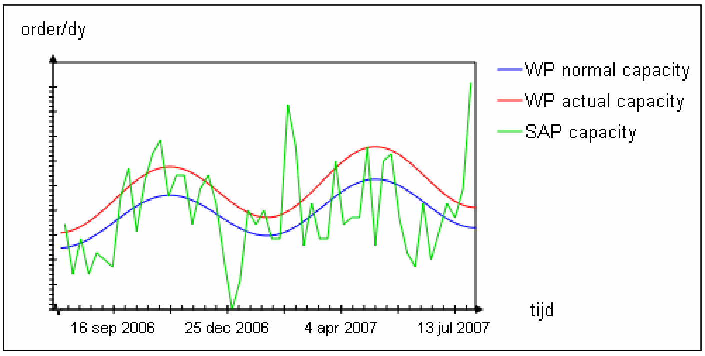

Figure 19: WP capacity estimation

During the Group Model Building sessions the participants mentioned the effect of *workload* on the capacity of the work preparation employees. When there are a lot of approved notifications (NOPR), especially those with a high priority, the employees can prepare more orders than with a normal amount of approved notifications. Sterman (2000) describes a way to model the effects of workload as capacity utilization by building a non-linear function. This structure was adopted in the model and determines the actual capacity based on the normal capacity that is available (see Figure 19) (Sterman 2000).

Purchase and scheduling

The needed materials are purchased by the purchase employees and the work orders are scheduled for execution. The schedule employees determine the time between the moment the necessary materials are expected to be present and the execution of the first operational step of the work order, when the work order is partly confirmed (PCNF).

As previously mentioned the process of purchasing materials is not adopted in the model, but the SAP cycle time (for each priority) between REL and PCNF is used to determine this process step.

The participants of the Group Model Building sessions mentioned that the purchase of materials determines this cycle time for approximately 80%.

The remaining 20% of the cycle time between REL and PCNF is determined by the schedule process. The schedule employees use several data to schedule the execution of the order. The expected delivery date of materials and the Latest Allowed Finished Date (LAFD), determined by the priority, prescribe the time window in which the order has to be executed. The expected execution time and the available capacity of the base crew determine the possibilities to schedule the execution in this prescribed time window.

The current data availability made it impossible to model the schedule process in the above mentioned way and therefore the schedule process is modelled with the 20% of the cycle time between REL and PCNF and can be influenced by a change in base crew (BC) capacity, which is modelled as the BC comparison factor and is explained in the work execution structure. The entire purchase and schedule sub model is presented in Figure 20.

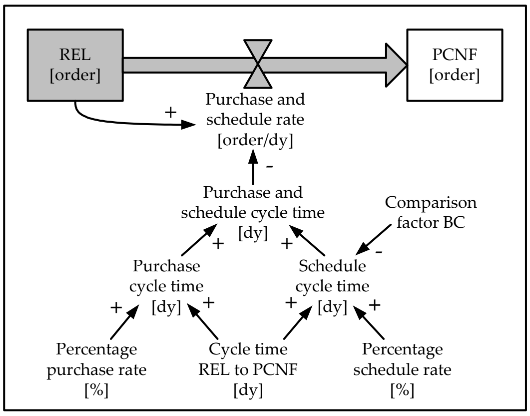

Figure 20: Purchase and schedule sub model

Work execution

The base crew employees execute the work orders and when all the operational steps are executed the work order is confirmed (CNF). Work execution is formulated in two sub models. The work execution capacity is determined by the BC labour force in the BC capacity generation sub model and allocated to the different priorities in the BC capacity allocation sub model.

BC capacity allocation

The allocation of the work execution capacity to the different priorities in PCNF is modelled in a similar structure as the WP capacity allocation sub model (Figure 16) and is presented in Figure 21. Capacity is claimed based on the number of orders in PCNF and the target execution delay. Whether the claimed capacity is also the allocated capacity depends on the available capacity. Priority 1 and 2 are directly executed and the remaining BC capacity is allocated to priority 3-7 according to the same structure as in the WP capacity allocation sub model in detail (Figure 17). The available capacity is not influenced by rework, because base crew rework is scheduled regularly and therefore has no priority above other orders. The specific rework structure is presented and explained in after the explanation of the work execution sub model.

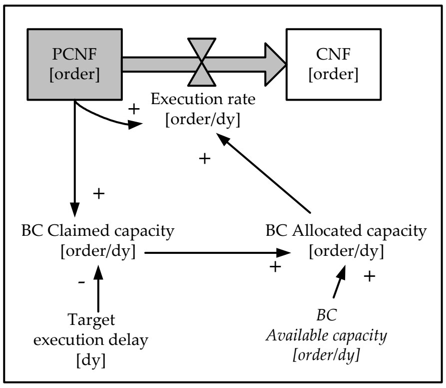

Figure 21: BC Capacity allocation sub model (main structure)

BC capacity generation

The execution of work orders is performed by the base crew and vendors (discussed at the end of this section) who execute work orders for Corrective (CM) and Preventive Maintenance (PM). The PM process is not in the scope of this study, but the influences of this process on the base crew capacity are considered.

The execution of CM considers both notifications of maintenance that need preparation of purchased materials, as well as notifications of maintenance that do not need preparation or purchased materials. Those that do not need preparation or purchased materials leave the regular

CM-process after the NOPR status, are coupled to yearwork orders (YWO) and are immediately executed by the base crew. The model only concerns the execution of work orders that follow the regular CM-process, so the execution of YWO is, just like the execution of PM orders, not in the scope of this study, but the influences of these YWO on the base crew capacity are considered.

The employees mentioned that the base crew employees do not have a different productivity and do not experience workload pressure as work preparation does. The only increase in productivity is caused by the fact that compared to the year 2006, smaller work packages are defined per order. Therefore the base crew relatively executes more orders, but the actual executed work remained the same.

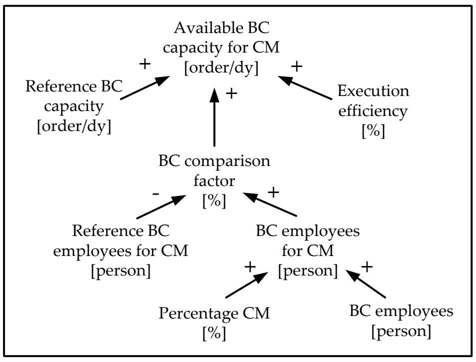

Figure 22: Main structure BC capacity generation

The BC capacity generation sub model is formulated in less detail than the WP capacity generation sub model. The main structure of BC capacity generation is presented in Figure 22 and described in this section.

Because of the previously mentioned reasons the *available BC capacity for CM* is determined by a reference BC capacity that is multiplied by a BC comparison factor and an execution efficiency percentage.

The reference BC capacity is determined by the number of executed orders in the reference period (01-08-2006 – 31-07-2007), divided by the length of this reference period (365 dys).

The BC comparison factor is determined by the current BC employees multiplied with the current percentage of CM, divided by the reference BC employees for CM. This enables the possibility to change the available BC capacity by changing the number of BC employees and the percentage BC capacity for CM. Changing the percentage of CM capacity can be realized by changing the percentage PM and YWO capacity. In the model this only affects the available BC capacity and not the execution of YWO and PM orders, because only the physical process of CM is modelled

The execution efficiency is not only determined by the base crew, but also by vendors. Vendors are hired for operations that are not executed by the base crew, but are necessary to execute the maintenance. They execute the preliminary steps, like building scaffolding and removing insulation, and the finishing steps, like adding insulation, painting and removing the scaffolding. Because these vendors are hired whenever they are needed, and their availability is quite high, there is no need to adopt these vendors and their capacity in the model. If their availability decreases, the influences of this drop in capacity on the execution process will have to be analyzed. Because orders in PCNF are already being executed, and this execution is not only performed by the base crew but also by vendors, a distinction can be made between base crew time and non-base crew time in PCNF. The execution efficiency percentage is determined by this BC and non-BC time in PCNF.

Rework

Sometimes when the base crew starts to execute a work order, they discover that the order cannot be executed because they have the wrong materials to perform the maintenance. In this case the system status is already set to partly confirmed (PCNF), because they already started to execute the order, and the order is sent back to work preparation for rework. The order is prepared again, materials are purchased and the order is executed instantly so the job can be finished. This rework process is not administrated in SAP, so these rework orders keep the system status PCNF. In the model an extra level is adopted (Rework PCNF) in which the rework orders are stored. The inflow of this level is determined by the rework generation sub model (see Figure 23) and the outflow is determined by the rework purchase and schedule rate of the rework process sub model (see Figure 24). These sub models are presented in the next sections.

Rework generation

The formulated rework generation structure is presented in Figure 23. The fraction of rework is determined by the work preparation quality and the quality of documents regarding the plant and installations. The quality of work preparation is influenced by the matter of experience of the WP employees and the experienced workload. Only a part of the total rework needs rework preparation and re-purchase of materials, the other part needs financial confirmation. Because this rework only affects the orders in CNF the financial confirmation rework is not adopted in the model.

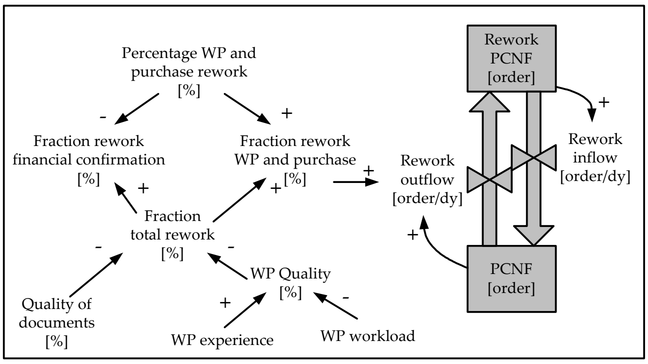

Figure 23: Rework generation sub model

Rework process

The participants in the Group Model Building sessions mentioned that rework is prepared instantly when the order is returned to the work preparation employee if there are no orders of priority 1 or 2, else these orders are prepared first. Therefore the amount of rework claims capacity of work preparation, which causes a decrease in the capacity available for the preparation of priority 3-7 orders of the regular CM-process. Rework preparation and the re-purchasing of materials takes less time than in the regular process and therefore the parameter values in this sub model differ from those in the WP capacity allocation and purchase and schedule sub models. The orders are executed instantly so scheduling does not cause a delay. The formulated rework process structure is presented in Figure 24.

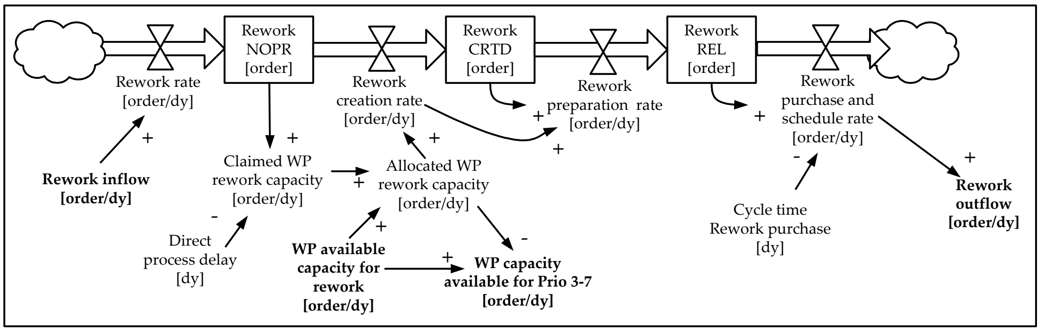

Figure 24: Rework process sub model

Feedback loop

In the rework structure a feedback loop can be identified (see Figure 25). The workload pressure of work preparation is determined by the number of orders that need to be prepared in the prescribed time window, and the available work preparation capacity. If the number of orders to be prepared increases, the workload pressure will also increase (assuming that the other influencing variables are constant). An increase of the workload pressure will result in a decrease of the quality of work

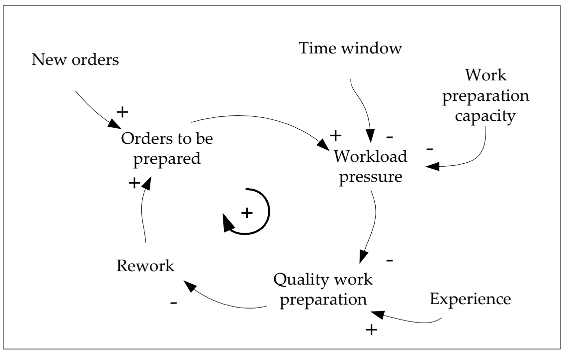

Figure 25: Rework work preparation

preparation (assuming the experience of the employees is constant). A low quality of the prepared order can result in rework, because the orders cannot be executed. Rework increases the orders to be prepared, which will increase the workload pressure. These defined relations cause a positive feedback loop that keeps increasing. The other factors that influence this feedback loop can change this behaviour. For instance, if there is more work preparation capacity, the workload pressure will decrease, which increases the quality and so on.

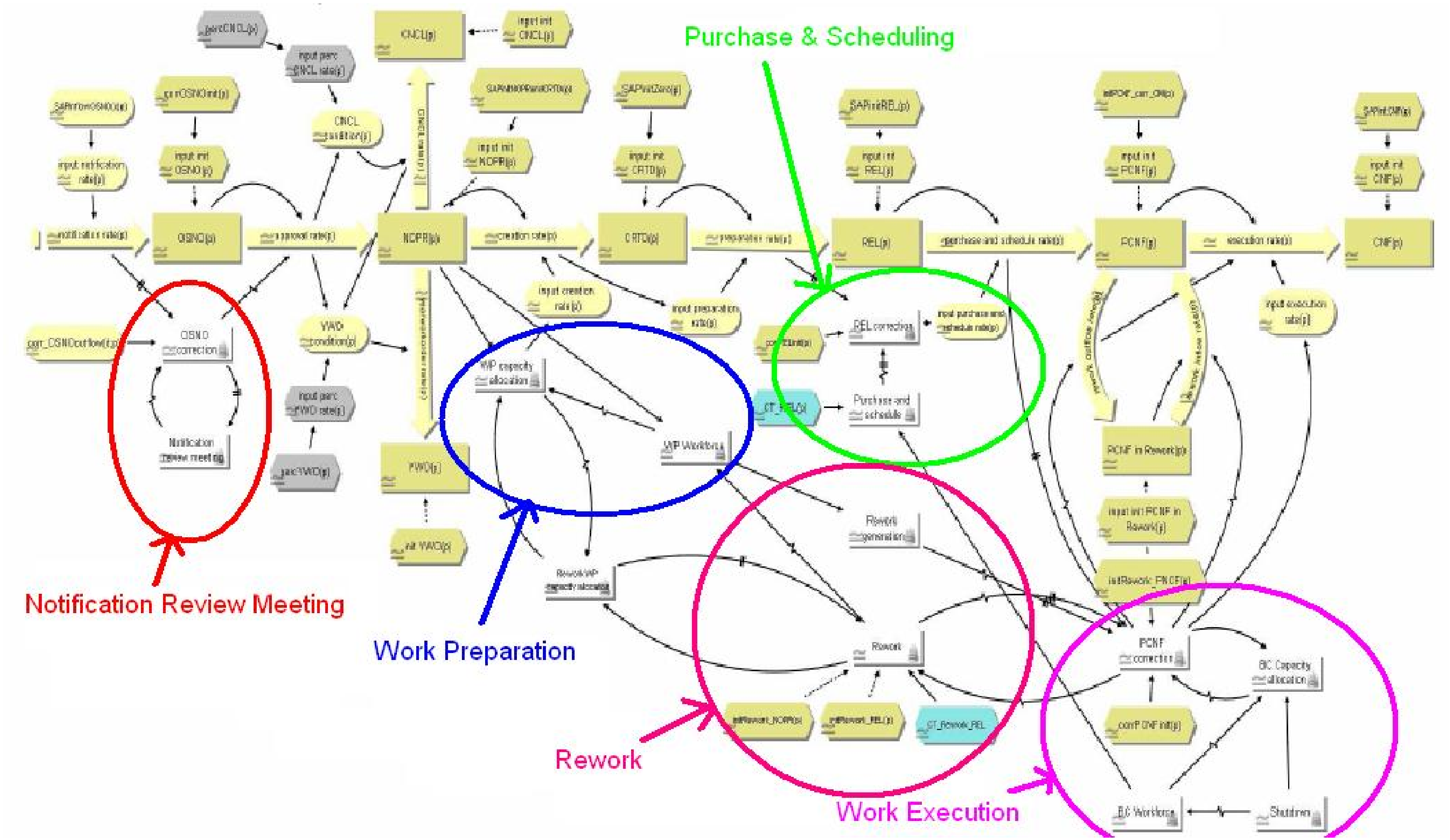

Figure 26: Model overview; interrelation of sub models