Evaluating Fleet and Maintenance Management Strategies through System Dynamics Model in a *City Bus Company*

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Abstract

The evolution of *fleet maintenance and management policies* highlights the growing importance of maintenance issues in both private and public companies. The need to improve maintenance performance requires an accurate evaluation of the trade-off between costs and benefits related to alternative fleet maintenance and management policies. However, the complexity of maintenance system makes this evaluation a very difficult task.
More often a fleet manager deals with the following key issues:

- *is it more profitable to repair or to renew the company fleet?*
- *Is it more convenient to reduce the average age of the different assets (e.g., by increasing investments in new bus) or to expand the maintenance activities (e.g., by rising repairing costs)?*

In fact, fleet managers cannot ignore the impact of their decisions on both company service and financial performance over time.
Aim of this paper is to show how the System Dynamics approach can effectively support fleet managers in designing and evaluating their strategies. The simulation model here presented is based on the result of a project with two Italian city bus companies. Through such tool decision makers can test different fleet strategies and assess their effects on company performance.

1. INTRODUCTION

Quite often companies running a public service, whose tariffs must be contracted in advance with the governmental authority, are not able to transfer any increase of their production costs on service price. As a consequence, in order to maintain a satisfactory business profitability such companies tend to postpone both current and strategic investments. Such approach may generate on the medium-log term side effects that could undermine future growth.
In fact, during a financial crisis current fleet maintenance program and maintainers training policies may be neglected as on the one hand their benefits are difficult to quantify and on the other hand their impact on company performance is not immediate. In the medium-long term, such behaviour may lead to a reduction in fleet availability and in the service provided to customers. Therefore, the short term benefits of the policies aimed to cut cost are counteracted by a strong decline in company revenues. These results may generate further difficulties in timely planning strategic investments, such as fleet renewal.
However, in the last decades, maintenance strategies have been evolving aiming "*to carry out as little maintenance as possible* [and] *as infrequently as possible while at the same time preserving the availability*"[1] of company assets. For this reason, managers have been forced to adopt maintenance planning and control systems to revise their policies more accurately. In particular, the aim of these tools is to support managers in identifying the most convenient maintenance policies in accordance with the breakdown patterns of the different assets.

[1] Horner, R.M.W., El-Haram, M.A. and Munns, A.K. (1997). "Building Maintenance Strategy: a New Management Approach". Journal of Quality in Maintenance Engineering, Vol. 3 No. 4, 1997, pp. 273.

In order to assess the effects of fleet maintenance and management policies on both assets reliability and availability, it is necessary to have a deep understanding of the failure pattern over time [2] : a) *infant mortality* (when the failure rates diminishes with time); b) *chance failure* (when the failure rate is constant over time) and c) *wear-out* (when the failure rate increases with time) [3].

As a consequence a fleet manager has to deal with the following key issues:

- *is it more profitable to repair or to renew the company fleet?*
- *Is it more convenient to reduce the average age of the different assets (e.g., by increasing investments in new bus) or to expand the maintenance activities (e.g., by rising repairing costs)?*

These questions underline the strong correlation between fleet maintenance and fleet renewal and the relevance of such policies on both company production and financial results.

In fact, fleet maintenance and management policies have to be considered as two interrelated key issues of the same planning process, whose objective is to guarantee the highest level of service at the minimum cost.

The complexity behind fleet maintenance and management activities cannot be overcome only by collecting past data and applying statistics models [4]. In order to understand and assess the robustness of company policies over time it is necessary to investigate the net of causality between fleet maintenance and renewal decisions and the dynamics of both failure behaviour and ageing process. Moreover, such causal relationships are characterised by delays and non-linearity.

Based on such remarks, System Dynamics (SD) methodology has been identified as a valid support to fleet maintenance and management.

In particular, as result of the study conducted with two major city bus companies (ATAF of Florence and ATC of Bologna), an SD model has been built in order to explore the effects of different fleet maintenance and management policies on business performance.

2. EVOLUTION OF MAINTENANCE POLICIES

Maintenance is commonly described as an activity intended to restore or keep an asset in a state in which it can perform its functions. In other words, maintenance can be portrayed as the set of actions carried out on an asset in order to ensure that the asset continues to perform its intended functions by repairing any equipment that has failed and/or by restoring it to its favourable operating condition.

Therefore, maintenance is aimed at reducing, in quantity and length, production process interruptions. This implies that the maintenance activity should increase the reliability of production assets by decreasing their failures. However, the objective of failure reduction does not probably yield the best results with regard to the financial objectives, because the costs of higher assets reliability may exceed the returns deriving from the consequent improvement of the production performance. As all company sub-systems, also maintenance has to be intended to increase company profits. Consequently, maintenance management should carefully evaluate costs and benefits deriving from the different maintenance policies. With this regard, Wireman[5] defines maintenance management as "*the management of all assets owned by a company, based on maximizing the return on investment in the asset*". The main objective of maintenance management,

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[2] It is worth remarking that failure behaviour also depends on the age of the assets.

[3] Abernethy, Robert B. (1996). The New Weibull Handbook Dr. Robert B. Abernethy, 536 Oyster Road, North Palm Beach, Florida.

[4] Sterman, J. D. (2000). Business Dynamics - System Thinking and Modeling for a Complex World. Irwin McGraw-Hill, pag. 67.

[5] Wireman, T. (1998). Developing performance indicators for managing maintenance. Industrial Press Inc., New York, USA, , pag. 1.

hence, is "*to reduce the adverse effects of breakdown and maximize the facility availability at minimum cost*" [6], with respect to both maintenance costs and production losses.

Over the past years, the importance of maintenance management within a firm has been growing. The rising competition and, hence, the necessity for a higher level of production efficiency on the one side, and the increasing concern on aspects such as risk-safety and environmental integrity on the other side, determined wider boundaries of the maintenance function and a greater necessity for better maintenance policies.

We can identify three major policies characterizing the evolution of maintenance management:

- Breakdown maintenance;
- Preventive maintenance;
- Condition based maintenance.

Breakdown maintenance represents the traditional maintenance policy. This way of doing maintenance is carried out by fixing production assets when they fail. Therefore, the maintenance activity is not scheduled.

This first generation of maintenance policies did not create any problem to the management of the companies during the earlier days of industrialization, which were characterized by a low level of technology. Most of the production assets, then, could be repaired in a very short time. Thus, downtime was short and maintenance did not represent a high priority issue.

Nowadays, because of the technological progress, production equipments are more complex. The maintenance activity is more difficult and special skills and more time are necessary to fix breakdowns. As a consequence, the unpredicted interruptions of the production process, due to breakdowns, last longer, determining customers' dissatisfaction.

Furthermore, breakdown maintenance presents other two main shortcomings[7]:

- the failure of an item can cause consequential damages to other parts of the equipment[8];
- the unpredictability of breakdowns can make manpower and spare parts planning extremely difficult.

For these reasons, in the sixties, a second generation of maintenance policies was introduced, preventive maintenance, which consists of planned maintenance tasks carried out at regular, fixed intervals, usually based on equipment's operating time or age. Preventive maintenance is based on the assumption that the average lifetime of an asset can be determined. Thus, by replacing it in correspondence of its average lifetime, the chance of breakdowns can be reduced.

In particular, preventive maintenance presents the following advantages[9]:

- maintenance can be planned and carried out when it is more convenient in accordance with production, customer and manpower need;
- generally, preventive maintenance determines a lower rate of failure, reducing, as a consequence, costs of consequential damages and downtime.

However, even preventive maintenance has some disadvantages that can offset the above-mentioned benefits[10]:

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[6] Lofsten, H. (1999). "Management of Industrial Maintenance – Economic Evaluation of Maintenance Policies". International Journal of Operations & Production Management, Vol. 19 No. 7, 1999, pp. 716.

[7] Horner, R.M.W., El-Haram, M.A. and Munns, A.K. (1997). Building maintenance strategy: a new management approach. Journal of Quality in Maintenance Engineering, Vol. 3 No. 4, pp. 273-280.

[8] "*In a multi-components system, the failures of each entity generally have an influence on the reliability behaviour of the other components. The failure of one components leads to the increase of the failure rate of the neighbouring components*". Pérès, F., Noyes, D. (2003). Evaluation of a Maintenance Strategy by the Analysis of the Rate of Repair. Quality and Reliability Engineering International, 19,129–148

[9] Raymond, C.M. and Joan, C.F (1991). Preventive Maintenance of Buildings. Chapman and Hall, London.

[10] See: El-Haram, M., Horner, R.M. and Munns, A. (1996). Application of RCM to building maintenance strategies. Proceedings of the 6th International Logistics symposium, UK, pp. 133-43. Chan, L., Mui, L., and Woo, C. (1997). Reliability analysis and maintenance policy of radiators for a large fleet of buses. Quality and reliability engineering international, vol. 13, 117–126.

- pieces of the equipment are replaced or remanufactured at a fixed intervals regardless of their condition at the time. This often turns out into a waste of resources since the replaced elements could have remained in a safe and acceptable operating condition for a much longer time.
- the replacement of an element before it reaches its "wear out" stage can increase the chance of failure because of "infant mortality".
- though preventive maintenance usually requires a large amount of spare parts and labour, it does not completely eliminate breakdowns.

With the intent of increasing asset availability keeping low maintenance costs, maintenance managers started devoting more attention to the analysis of the failure mode of the different elements of an asset and their effects on the production system performance, the so called Failure Mode Effects and Criticality Analysis (FMECA). The concept of Reliability Centered Maintenance (RCM) started spreading: a customized preventive maintenance is planned for the different items, eliminating those activities that are not essential to keep the production system in the desired operating conditions.

This mindset change led to a new generation of maintenance policy, the condition based maintenance (CBM), which is defined as: "*Maintenance carried out in response to a significant deterioration in a unit as indicated by a change in monitored parameter of the unit condition or performance*"[11]. CBM can be performed only if the state of the system is constantly checked. This is often done by installing sensors in different parts on an asset in order to detect critical signals of potential failure (i.e., increase in vibration or temperature) and intervene before the failure actually occurs.

However, CBM presents some disadvantages:

- it involves a tremendous amount of resources, time, and energy and, hence, it is not always cost-effective;
- though "*conditional maintenance proves to be very efficient for certain components which emit precursor signs of failure*"[12], this maintenance policy is inadequate for others. Some studies, for example, point out some difficulties of applying CBM on a moving system, such as a rail vehicle[13];
- for some critical items, condition monitoring techniques may not exist.

Which one of the above three types of maintenance policies should be chosen?

To answer this question we should consider that the main objective of maintenance management is to increase availability at minimum costs. Scholars affirm that "*every maintenance intervention scheduled earlier or later than the optimal time increases the maintenance cost*"[14]. As we have seen, on the one hand an excess of maintenance activity implies high total costs, on the other hand a scarce maintenance activity determines a higher probability of failure and, hence, greater total cost due to emergency interventions.

Therefore, in order to select the best maintenance policy to perform an attentive analysis of the failure mode, of the consequential costs, and of operational convenience and practicality should be carried out.

Breakdown maintenance is convenient when the cost of failure is low, the cost of maintenance is high, and the rate of failure does not increase with time. On the contrary, preventive maintenance or CBM should be chosen when the cost of failure is high and the rate of failure increases with time. In such a case, CBM should be preferred to preventive maintenance if the cost of detection of signs of failure is relatively low. In conclusion, the opportune to adopt a type of maintenance policy varies

[11] Kelly, A. and Harris, M.J. (1978). Management of Industrial Maintenance. Butterworths, London.
[12] Kelly, A. and Harris, M.J. (1978). Management of Industrial Maintenance. Butterworths, London.
[13] Bengtsson, M., "Condition Based Maintenance on Rail Vehicles", IDPMTR 06 (2002).
[14] Lofsten, H. (1999). Management of industrial maintenance – economic evaluation of maintenance policies. International Journal of Operations & Production Management, Vol. 19 No. 7, 1999, p. 733.

according to the characteristics of the different assets to maintain. If economically opportune, an appropriate strategy should be selected for each item of the asset[15].
The FMECA could support the management in the identification of the maintenance policy to adopt, but this analysis may result time consuming and expensive. Quite reliable information about the failure mode of the different assets to maintain can be more easily obtained by interviewing the most expert maintainers within the company.
As for the costs of the different maintenance policies, manager should take into account not only "visible costs", such as labour, materials, services, and maintenance overhead costs, but also "hidden costs", which are more difficult to detect and measure, such as unplanned production process interruption losses, operating losses due to customer dissatisfaction, over capacity[16].
The difficulty of carrying out costs and benefits analysis for the different maintenance policies, considering both visible and hidden costs and their effects on asset availability, points out the need of maintenance managers for planning and control systems that support them in the policy design process. Such tools should help maintenance managers to evaluate the effects of the different policies on the performance of the maintenance sub-system and of the company as a whole.

3. A SYSTEMIC APPROACH FOR MAINTENANCE MANAGEMENT

In the previous paragraph, it was remarked that in the maintenance policy design process, managers should analyse the trade-off between costs and benefits of the different maintenance plans in order to enhance the performance of the company as a whole. This objective implies the necessity for the maintenance management to consider not only the effects of their policies in terms of asset availability and maintenance costs, but also their consequences on the performance of other company's sub-systems. For this purpose, maintenance managers have to adopt a systemic approach in order to analyse the cause-and-effect relationships between the different firm's areas.
Maintenance, in fact, is strictly correlated with other company's sub-systems, in particular:

- production,
- finance,
- asset management,

Production is the business area that is most directly related to the maintenance sub-system. Maintenance, in fact, can be considered as part of the production process: on the one side maintenance affects production capacity, on the other side production creates maintenance need.
However, "*historically, the relationship, between maintenance and production has been characterized by conflict*"[17]. Preventive maintenance activity is normally considered a constraint of the production process. For this reason, companies tend either to reduce preventive maintenance with negative effects on system reliability or to increase the number of spare machines, in order to reduce stoppages of the production process due to breakdowns, sensibly increasing investment costs.
The relationships of maintenance with the financial area are apparently obvious: on the one hand, the maintenance activity produces costs that reduce company's operating profits and liquidity, on the other hand, maintenance policies are budget driven.
However, if we analyse these relationships more in detail, we can perceive that they are not so obvious. In fact, maintenance managers can improve financial outcomes by increasing maintenance efficiency and, hence, either by reducing costs while keeping the same level of availability or by rising availability with the same level of costs. A greater level of availability, in fact, implies better production performances, which determine higher customer satisfaction and, eventually, revenues.
With regards to the influence of finance on maintenance, generally "*maintenance is not carried out according to actual needs, but is dictated by financial priorities*". In particular, the continuous

[15] Raymond, C.M. and Joan, C.F (1991). Preventive Maintenance of Buildings. Chapman and Hall, London.
[16] File, T. (1991). Cost effective maintenance: design and implementation. Oxford, UK, Butterworth- einemann Ltd.
[17] Lofsten, H. (1999). Management of industrial maintenance – economic evaluation of maintenance policies. International Journal of Operations & Production Management, Vol. 19 No. 7, 1999, p. 718.

research of higher productivity often leads managers to a hard cut-costing activity, which determines a reduction of budgets for planned maintenance[18]. If in the short term this policy reduces maintenance costs, in the longer term maintenance performance sharply drops. In fact, a reduction of preventive maintenance increases the probability of failures. An augment of breakdowns diminishes maintenance department's capacity to maintain or improve the production system on a regular basis. *"In the long run, the vicious circle "Repairs eat up Prevention" results in a situation with many unexpected machine breakdowns and an overloaded maintenance department"*[19].
These relationships highlight the importance of considering medium and long-term effects in the policy design process.
Asset management has a strong influence on the performance of maintenance activity. The brand mix of the different assets, the average age of the equipments, the level of technology are factors impacting on asset reliability, maintainability and, hence, availability. Asset managers, therefore, have to carefully evaluate the different acquisition policies not only by comparing crude purchasing costs by also considering the effect of their choices on maintenance capacity and costs to restore the different assets in their intended operating conditions.
For example, Rolls Royce automobiles have a good reputation for high reliability, but the lead-time for spare parts may be long so that, when a failure occurs, the Mean Time To Repair (MTTR) will be extended and, thus, availability will be low,[20] as well as maintenance performance.
Furthermore, a reduction of the average age of the equipment implies high investment costs, but these costs may be offset by a considerable reduction of maintenance costs due, for example, to a lower failure rate.
The importance of the relationships between asset e maintenance management has been widely recognised both in literature and practice. Maintenance costs represent a relevant percentage of the total costs a company has to bear for the entire life of an asset. As a consequence, purchasing decisions based only on acquisition costs may reduce expenses in the short term but repercussions may be experienced later in the form of increased breakdowns and unavailability. For this reason, the concept of Life Cycle Cost (LCC) was developed. Conceived in the sixties, life cycle costing is a technique for the analysis of the total costs a company forecasts to sustain for the acquisition, operation, maintenance, and disposal of an asset over its expected useful life span.
The life cycle concept "*helps managers to understand acquisition costs vs. operating and support costs, i.e. to find a correct balance between investment costs vs. operating expenses*"[21]. In particular, LCC creates "*awareness among the managers to produce an effective system with not only a low acquisition cost but also low operation, support and disposal costs*" (Sherif, Y.S.,1982).[22]
However, this approach presents some drawbacks[23].
In particular, LCC models require cost databases, which often are not available or accurate. Manufacturers may provide LCC models, however, these must be treated with caution especially if they are not contractually binding.
Furthermore, LCC does not explicitly consider the effect of ageing on the model variables, the costs of breakdowns in terms of opportunity losses, the effect of learning curves on maintenance costs, and so on[24].

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[18] Cattaneo, M. (2003). Maintenance in crisis phases (original title: La manutenzione in tempi di crisi), presented at Forum dei Manager di Manutenzione 2003, Milan.
[19] Thun, J. (2004). Modelling modern maintenance – a System Dynamics model analyzing the dynamic implications of implementing total productive maintenance. Presented at 22nd International System Dynamics Conference, Oxford.
[20] Mulder, D. (2003). Reducing Maintenance Time: An Alternative to Increasing System Reliability. Presented at Second Annual Hawaii International Conference on Statistics and Related Fields, Hawaii .
[21] Susman G (1989) Product life cycle management. Journal of cost management, vol. 3, Summer, p 8-22.
[22] Sherif, Y.S. (1982), An Optimal Maintenance Model for Life-cycle Costing Analysis, Reliability Engineering, vol. 3, pp. 173-177
[23] Barringer, H., Weber, D. (1996). Life Cycle Cost Tutorial. Fifth International Conference on Process Plant Reliability, Marriott Houston Westside Houston, Texas

To deeply perceive the relationships between maintenance and asset management we also need to consider how maintenance performance affects purchasing acquisitions. In fact, an improvement of maintenance efficiency determines a higher availability and, thus, a reduction of spare equipments the company needs to ensure an adequate level of production service.

By the light of these relationships, it is easier to understand how a coordinated set of maintenance and asset management policies, can reduce investments costs while guarantying a satisfying level of availability.

Maintenance management also comprehends human resources functions. Maintenance managers, indeed, have to achieve availability targets within their manpower capacity constraints. In the policy formulation process, then, the management has to take into consideration the maintenance workforce productivity. In particular, maintenance managers have to identify potential managerial levers to act on in order to increase such productivity while keeping an eye on labour costs. Thus, with a certain maintenance equipment, maintenance managers has to take decision relative to maintainers hiring, turnover, training, overtime, and so on. Moreover, in the decision making process the management has to consider the trade-off between maintenance capacity and costs, considering maintenance targets and firm's overall goals.

Nowadays, many companies tend to contract out the maintenance service. The logic behind maintenance outsourcing is that firms that have maintenance as their core business achieve higher performances in terms of productivity and efficiency. Companies, then, buy the maintenance service from external maintenance firms to reduce their maintenance costs, to close maintenance capacity gaps, and to lower maintenance management complexity.

However, maintenance outsourcing presents some side-effects.

First of all, maintenance contractors lack a long-term view that embraces the entire life span of the assets. Consequently, they tend to ignore maintenance activities addressed to improve the working conditions of company's assets.

Furthermore, maintenance outsourcing may imply an impoverishment of the company know-how. By contracting out the maintenance of equipments with high level of know-how, companies tend to invest less in maintainers training, reducing, in the longer term, their skills.

As a consequence, the advantages of maintenance outsourcing shrinks when the level of know-how of the maintenance activity to contract out increases. This relationship is even stronger if we consider that the cost of maintenance outsourcing increases when the required level of know-how is higher.

The analysis of the different relationships between maintenance an the other company sub-sectors points out the necessity for the maintenance management to adopt a wider view in the decision making process. In particular, we have discussed the importance of evaluating the coherence between maintenance targets and firm's corporate goals and the effects of managerial decisions both in short and long term. The consideration in the planning process of the systemic relationships with the other firm's management areas and of a medium-long time horizon marks the boundary between maintenance policies and maintenance strategies.

However, firms do not implement such a systemic approach. In fact, scholars sustain that there is a lack of linkage between maintenance objectives and the overall corporate strategy due to the adopted performance measurement systems[25]. In particular, the most common maintenance performance indicators enable the management to monitor only the operational perspective of the maintenance activity, while ignoring the effects of the maintenance policy on the performance of the other firm's sectors. Some authors affirm that a performance measurement system based on the casual relationships between the different company sub-areas facilitate the communication process

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[24] As we will see later most of these faults may be overcome by using a System Dynamics approach.

[25] Kutucuoglu, K.Y., Hamali, J., Irani, Z. and Sharp, J.M (2001). A framework for managing maintenance using performance measurement systems. International Journal of Operations & Production Management, vol. 21, n° 1/2, pp. 173-174.

between the "*corporate strategy and the different hierarchies of the maintenance organisation*"[26]. This leads to an alignment between maintenance and corporate objectives.
With this purpose, some authors [27] suggest to adopt the Balanced Scorecard [28] approach for maintenance strategy formulation. The systemic perspective of the Balanced Scorecard, in fact, supports the management in the analysis of the different relationships between the maintenance sub-system and the other business area in order to avoid that performance improvements in maintenance management are achieved at the expenses of the performance in other company sub-sectors.

4. SYSTEM DYNAMICS MODELS TO COPE WITH COMPLEXITY IN MAINTENANCE MANAGEMENT

As we have seen in the previous paragraph, maintenance can be considered as a system that is correlated to other company sub-sectors by cause-and-effect relationships, which produce consequences both in the short and long term. For this reason, maintenance managers should not only individuate the right maintenance policy, but also adopt a wider perspective in order to design a maintenance strategy that is coherent with corporate goals.
The relevant number of causal relationships between maintenance and other company sub-sectors make strategy formulation for maintenance management a quite difficult task. Although it may be possible for maintenance managers to identify all the relevant causal relationships between maintenance and the other business areas, it is hard to take into account all of these cause-and-effect relationships at the same time and to envisage the impact of maintenance strategy on corporate performance. In fact, we have seen how maintenance objectives may conflict with each other.
Such a difficulty turns into complexity if we consider that most of these relationships are not linear and that delays exist between causes and relatives effects. Moreover, various interests have to be taken into account in the design of the maintenance strategy, for example, the local government's concern about environmental policies and investment funding, customers' sensibility about the quality of the service, workers' attention about safety and comfort.
Therefore, because of the complexity characterising maintenance systems, the analysis of costs and benefits relative to the different maintenance decisions is problematic. As for the study of maintenance costs, we have already said that managers have to consider both visible and hidden costs, including "soft" variables such as company image, customer satisfaction, and workers' motivation. Also benefits are difficult to quantify because of non-linear relationships between system key-variables (for example the effect of maintainers training on their productivity and, hence, maintenance capacity) and because of delayed effects of maintenance decisions (for instance, preventive maintenance is more expensive than corrective maintenance in the short term, but it may be much less expensive than corrective maintenance in the long term[29]).
Even if the maintenance management could have all the data about costs and benefits related to different maintenance strategy alternatives they would have difficulties in using these data. In fact, according to the theory of "*bounded rationality*"[30], the human mind can process only a limited number of information. In fact, in order to take into account all the relevant data in the decision making process, most maintenance managers use different maintenance planning tools.

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[26] Kutucuoglu, K.Y., Hamali, J., Irani, Z. and Sharp, J.M (2001). A framework for managing maintenance using performance measurement systems. International Journal of Operations & Production Management, vol. 21, n° 1/2, pp. 173-174..
[27] Tsang, A.H.C. (1998). A strategic approach to managing maintenance performance, Journal of Quality in Maintenance Engineering, vol. 4, n° 2, pp. 87-94. See also Liyanage, J. P., Kumar, U. (2003). Towards a value-based view on operations and maintenance performance management. Journal Of Quality In Maintenance Engineering, vol. 9, n° 4.
[28] Kaplan, R.S. and Norton, D.P. (1996). Translating strategy into action – the Balanced Scorecard. Harvard Business School Press, Boston, Massachusetts.
[29] Sterman, J. D. (2000). Business Dynamics - System Thinking and Modeling for a Complex World. Irwin McGraw-Hill.
[30] Simon, H. A.(1950). Administrative Behavior. MacMillan, New York.

However, "*these tools tend to focus on the detail complexity of the maintenance challenge, for example, databases to track the maintenance history of each individual piece of equipment, statistical models to optimise maintenance schedules, scheduling systems to assigns mechanics to planned and reactive work, and so on*"[31]. Although, these instruments may be very useful for the daily operating management of the equipments they do not capture the dynamic complexity of the entire maintenance system. For this reason is opportune to associate to the use of these operating tools System Dynamics (SD) models, which offer to the management of the company a valid support for the comprehension of the complexity of the maintenance system.

SD associates to a qualitative analysis of a system feedback structure a quantitative modelling process, which adopts differential equations to investigate the dynamics of the examined system according to a stock-and-flow perspective.

The analysis of the system structure is essentially based on managers' mental models, through which it is possible to investigate the cause-and-effects relationships between the key-variables of the system. The quantitative simulation model supports the management in understanding the potential impact of managers' decisions on system performance. In particular, the use of a SD model helps managers in:

- obtaining a deeper comprehension of the causal structure underlying the entire company system;
- taking into consideration delays between actions and their effects;
- assessing non-linear effects on crucial system variables;
- identifying a set of policies in order to meet the targets in all of the corporate sub-areas.

In addition, the SD model can help managers to communicate their strategies both to internal and external stakeholders. System dynamics, indeed, offers an understandable language for describing the feedback structures characterising the system, so that stakeholders can easily realise the relationship between the structure and the related behaviour.

Moreover, SD models offer to managers a virtual word where they can test their hypotheses and evaluate the probable effects of their strategies without bearing the costs and risks of experimenting with them in the real world. In particular, SD models provide a "*low-cost laboratories for learning*"[32], where:

- time and space can be compressed or dilated;
- actions can be repeated under the same or different conditions;
- dangerous, infeasible or unethical strategies can be experimented in safe conditions;
- the information delays of feedbacks from the adopted decision are extremely reduced.

Finally, through an interactive periodical information exchange and comparison among accounting and System Dynamics models, managers can be aware of discrepancies between formal and mental models. This procedure can lead to corrections of the way mangers understand reality and, thus, boost their learning process.

5. THE SYSTEM DYNAMICS APPROACH APPLIED TO FLEET MAINTENANCE AND MANAGEMENT

In the literature already exist some applications of the SD methodology to the study of the maintenance system[33]. Our objective is to give further evidence of the advantages deriving from the application of SD models in the maintenance strategy design process for city bus companies.

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[31] Sterman, J. D. (2000). Business Dynamics - System Thinking and Modeling for a Complex World. Irwin McGraw-Hill

[32] Sterman, J. D. (2000). Business Dynamics - System Thinking and Modeling for a Complex World. Irwin McGraw-Hill

[33] See: Sterman, J. D. (2000). Playing the maintenance game. In Sterman, J. D. (2000). Business Dynamics - System Thinking and Modeling for a Complex World. Irwin McGraw-Hill, pp. 66 - 79. Crespo-Márquez, A., Usano, R. R. (1994). Learning Maintenance Management through System Dynamics. Paper presented at the 1994 International System Dynamics Conference, Sterling, Scotland. Mashayekhi, A. N. (1996). Oscillation in Preventitive Maintenance Programs. Paper presented at the 1996 International System Dynamics Conference, Cambridge, Massachusetts.

For this reason, Business Dynamics, an Italian consulting firm we work for, started a project with two Italian city bus companies (ATAF of Florence and ATC of Bologna) aimed to develop a SD model that could support the management in the maintenance decision-making process.

The research methodology

The research methodology, adopted to implement the project, was outlined as follows:

- the existing literature on maintenance and SD applied to fleet maintenance and management was analysed;
- interviews to fleet and maintenance managers of the two city bus companies were conducted;
- a SD model to support the strategy design process in maintenance management was developed.

The literature analysis allowed us to focus on the relevant topics for which SD is a suitable approach. As referred in the previous paragraphs, different studies point out the necessity to match maintenance management with corporate strategy. However, the lack of relevant data, the great number of interactions between maintenance and other company sub-sectors, the significance of delays and non-linear relationships characterising the complexity of the maintenance system make strategy design a very difficult task. A SD model, therefore, can support maintenance managers in the understanding of system complexity and, thus, in the formulation of a strategy that is coherent with corporate objectives.

The interviews to fleet and maintenance managers of the two city bus companies enabled us to analyse in more details the cause-and-effect relationships between the key-variables of the maintenance system and the interactions with the other company sub-sectors. The aim of these interviews was to capture the know-how of the company experts in the field of asset and maintenance management by eliciting their mental models. In particular, we focused on the main objectives of asset and maintenance managements, the performance indicators that are in use to measure and evaluate company results and the policy levers the management can act on to achieve the indicated objectives.

The interviews allowed us to share with the management a causal loop diagram that describes, in qualitative terms, the cause-and-effect structure underlying the maintenance system, with particular focus on the relationships between objectives, performance indicators and policy levers. The fleet and maintenance managers of ATAF and ATC revised this casual loop diagram and a common view of the system reality was achieved.

The third stage of the research process implied the "translation" of the causal loop diagram in a simulation model, based on the concept of stock-and-flow dynamics, by means of differential equations that describe the causal relationships represented in the qualitative analysis.

Through SD modelling is possible to transfer maintenance managers' knowledge to a computer that can process relevant information about the maintenance system, which have been captured by the casual loop diagramming, and simulate the effect of alternative maintenance strategies on the selected performance indicators. With this purpose, the SD model was subjected to some structural and behaviour tests. In particular, extreme condition tests allowed us to check the model's robustness. Furthermore, together with the city bus managers we analysed the result of different simulations to verify the coherence and the reliability of the SD simulation model.

The structure of the simulation model

The simulation model consists of five main sectors:

- a *guided introduction*, including the main variables relationships behind the simulation model (see causal loop analysis);

- an *input Excel file*, which allows the user to customise the simulator, according to different issues, such as: numbers of buses per categories, average bus age, desired level of bus service in terms of average service frequency, obsolescence time, annual breakdowns, ticket price, etc.;
- a *control panel* embodying main policy levers (e.g. bus renewal, maintenance scheduling, service management) (see figure 1a);
- *graphs and reports* including main variables impacting fleet maintenance and management performance e company results (see figure 1b);.

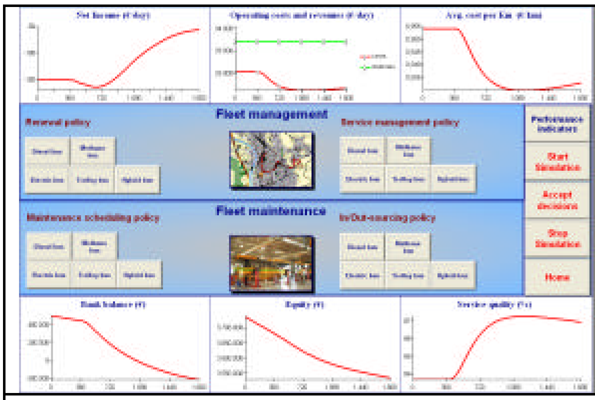

Figure 1a - An excerpt of the simulator *control panel*

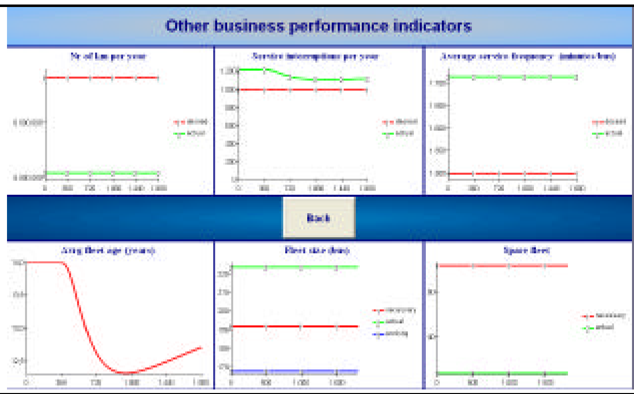

Figure 1b - Main variables impacting on fleet maintenance and management performance

Causal feedback loop analysis

Causal feedback loop analysis was focused on four correlated areas:

- fleet management,
- maintenance scheduling,
- maintenance capacity management,
- service management.

For each of the four managerial areas we identified the related policy levers and analysed their impact on the performance of the maintenance system by also considering financial results and service quality indicators.

In particular, in the fleet management area we took into account fleet renewal policies and fleet sizing policies. As we can see in the relative casual loop diagram represented in figure 2, a renewal policy reduces the average age of the bus fleet and, thus, this policy has, in general, a positive impact on the failure rate. A reduction of the failure rate reduces maintenance costs (loop R2), with a positive impact on company income. It also increases bus availability (loop R3), which determines a higher service frequency and, then, quality.

However, the renewal policy implies costs. First of all investment costs, which determine higher bus depreciation and, hence, lower profits (loop B1). Moreover, the renewal policy may be funded with external financial resources, which have a cost that reduces the income (loop B3).

A similar analysis can be related to the fleet sizing policy.

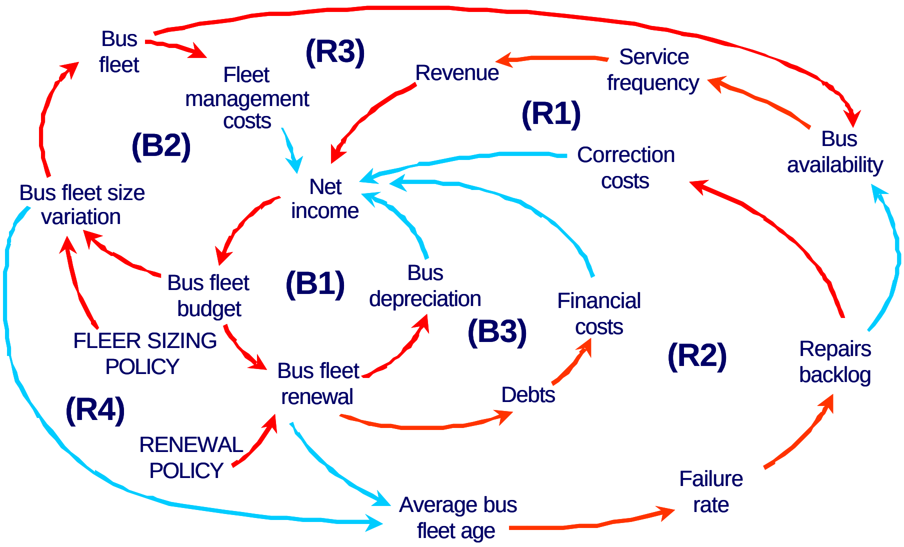

Fig. 2: the asset management casual loop diagram

In the maintenance scheduling area we considered, as a policy lever, the possibility for the management to decide the number of vehicles to stop for preventive and corrective maintenance. In fact, when the maintenance management, in accordance with the service management, plan the maintenance activity, it has to take into account how many vehicles will not be available for the daily service because of preventive and corrective maintenance. A reduction of bus stoppages for maintenance activity determines a higher vehicles availability and, hence, a better service (loop R6).
However, a reduction of bus stoppages involves a higher maintenance capacity in order to perform the required preventive and corrective maintenance. This causes higher maintenance costs (loop B5). In fact, if maintenance is contracted out, a reduction of bus stoppages determines an increase of the costs of the maintenance service. If maintenance is internally carried out, a reduction of stoppages can be obtained by more overtime hours and/or night work and/or maintainers.

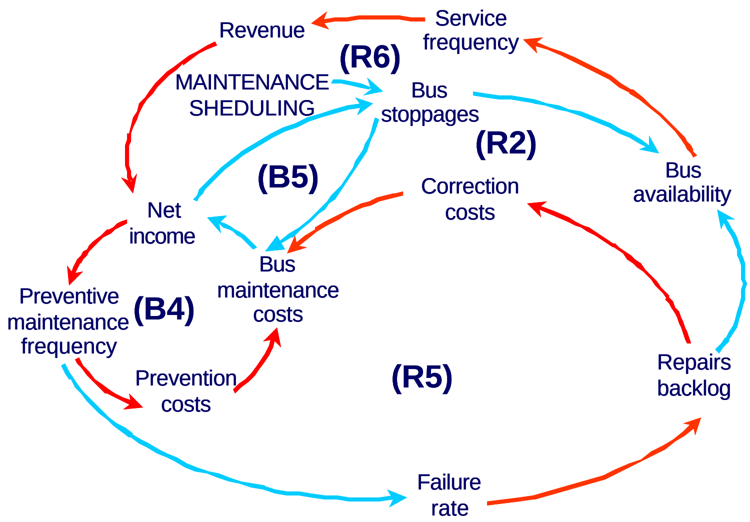

Fig. 3: the maintenance scheduling casual loop diagram

In the maintenance capacity management area we considered the following policy levers:

- maintainers hiring;
- overtime hours;

- out-sourcing;
- maintainers training.

The first three policy levers increase maintenance capacity, but, at the same time, they determine higher maintenance costs. As for the training, we distinguished maintainers in standard and experts according to their skills and, then, we assumed that experts dedicate part of their time to train standard maintainers. This implies, on the one hand, an increase of the number of standard maintainers that become experts and, thus, higher maintenance capacity; on the other hand, a reduction of the time that experts dedicate to maintenance activity.

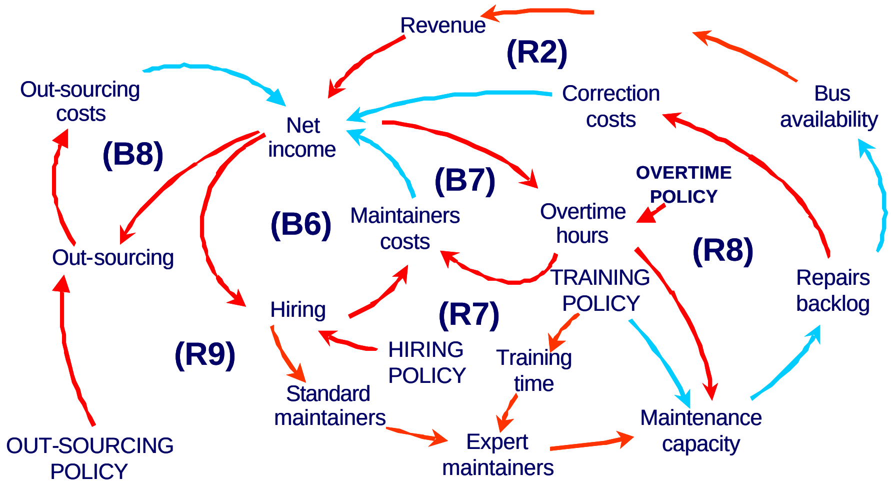

Fig. 4: the maintenance capacity management casual loop diagram

Finally, in the service management area we took into account the possibility for the management to redistribute the bus fleet among the different city lines to serve. The management, in fact, has to allocate the different sub-fleets, which have diverse motorizations and/or diverse size, according to the characteristics of the city lines and the requirements of the service contracts. Furthermore, the management may decide to redistribute the sub-fleets to reduce the production costs (loop R10), such as fuel costs. However, the redistribution of the bus fleet may have relevant consequences on maintenance activity.

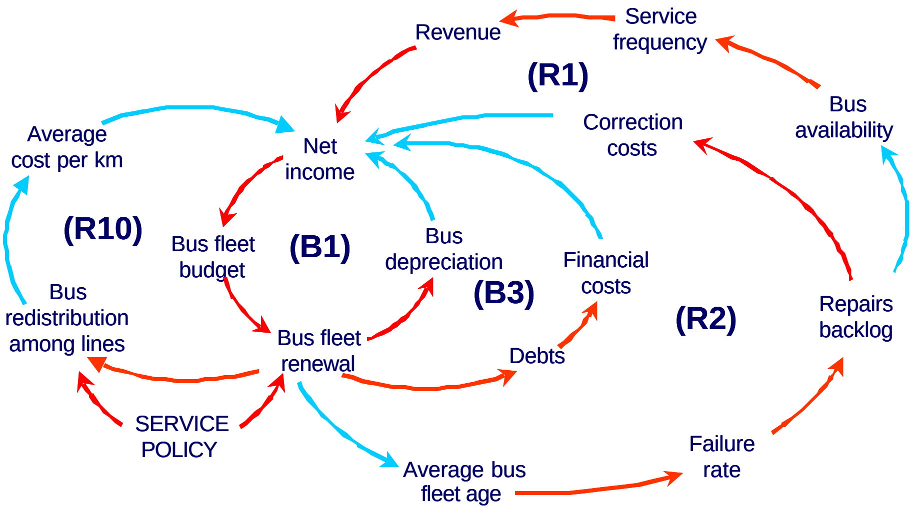

Fig. 5: the service management casual loop diagram

The SD model for the evaluation of city bus maintenance strategies

As we have previously said, SD modelling offers a laboratory where managers can test their strategies in a safe computer environment without bearing the risks of implementing potentially dangerous strategies in the real world.

By analysing simulation results, managers can improve their understanding of the potential effects of their policy levers on corporate performances. This is a relevant support for the management to identify the policy levers to act on and how to combine different policy levers to formulate a systemic strategy.

The following is an example of how an SD model can help the maintenance management of a city bus company to choose among alternative maintenance strategies. In particular, after experimenting different maintenance strategies, we identified three of them that determined a performance improvement of the hypothetical company we simulated. These three strategies are formulated as it follows:

- the first strategy implies a renewal of 3 vehicles (out of 28) per each sub-fleet, a reduction of stoppages from 3 to 1 bus per each sub-fleet for preventive maintenance and from 3 to 2 buses for corrective maintenance, and outsourcing of preventive maintenance for buses with diesel oil engine;
- the second strategy implies a renewal of 3 vehicles (out of 28) per each sub-fleet, a reduction of stoppages from 3 to 1 bus per each sub-fleet for preventive maintenance and from 3 to 2 buses for corrective maintenance, outsourcing of corrective maintenance for buses with diesel oil engine, and no maintainers turnover;
- the third strategy implies a renewal of 2 vehicles (out of 28) and an increase of 1 bus per each sub-fleet (determining a new total of 29 vehicles per each sub-fleet), a reduction of stoppages from 3 to 1 bus per each sub-fleet only for preventive maintenance, outsourcing of corrective maintenance for buses with diesel oil engine, and no maintainers turnover.

As the reader can notice, the three strategies are similar, but as we will see in the following figure, few changes in a maintenance strategy may lead to quite different results. In figure 6 are shown the simulation results of the three strategies with regards to four performance indicators: net income, average operating cost per km, cash, and service quality (which is calculated considering the respect of three service contract requirements: service frequency, service interruptions caused by breakdowns, total yearly km of service effectively produced).

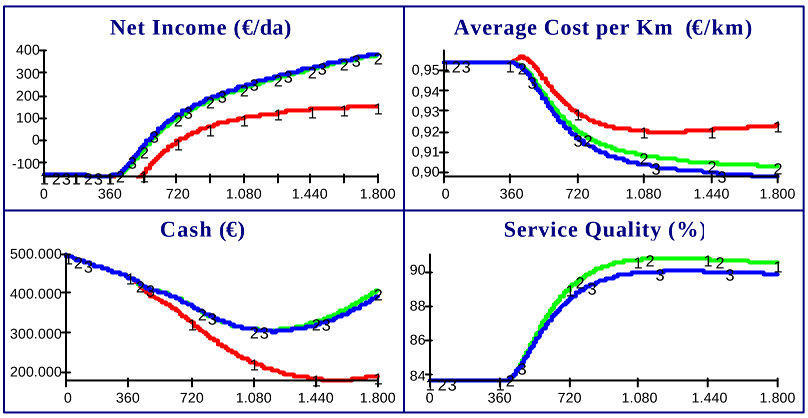

Fig. 6: simulation results of the three maintenance strategies

The first strategy (represented by he line number 1), which is very similar to the second strategy (represented by the line number 2), determines a good performance in terms of service quality, but it produces economic and financial results that are sensibly lower compared to the other two strategies. The reason of such a result can be identified in a mistaken evaluation of the outsourcing policy. In fact, by contracting out part of the maintenance activities, the management determines in the simulated company a surplus of maintenance workforce and, thus, the company has to bear double costs: the maintenance outsourcing costs and the costs of the excess maintenance workforce. This aspect has been correct in the second strategy, which guarantees the same level of quality while yielding better financial and economic results. The third strategy (represented by the line number 3) leads to economic results that are slightly better than the second strategy. However, the third strategy produces moderately lower financial results and a poorer service quality. The choice between the second and the third strategy depends on the vision of the company and on other considerations, not included in the SD model, about their feasibility.

Conclusions

The fleet maintenance system is strictly correlated with the other company areas. In order to align maintenance objectives with corporate goals, all these interrelationships should be considered. However, the relevant number of causal relationships between the maintenance system and the other company sub-sectors, the existence of delays between policy implementation and relative effects on the system performance, the presence of non-linear relationships between some key-variables of the system, make maintenance strategy formulation a very complex task.

The use of SD models can support the management in the cost and benefit analysis that is necessary to evaluate alternative fleet maintenance and management strategies. In particular, the SD approach allows managers to examine the potential impact of the different strategies on maintenance and corporate performance, considering both financial and qualitative aspects.

In particular, in the city bus sector we have seen how the SD models can help asset and maintenance management in combining the different policy levers to assure an adequate level of service without ignoring financial implications. Furthermore, city bus companies can use the SD models to communicate their strategy to their stakeholders, such as local government, financial institutions and citizens.

In conclusion, the results of this study give further evidence of the potentiality of the SD models as supporting tools for the evaluation of fleet maintenance and management strategies.

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