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A FRAMEWORK MODEL FOR ASSET MAINTENANCE MANAGEMENT

By Mohammad A. Hassanain[1], Thomas M. Froese[2], Member, ASCE, Dana J. Vanier[3]

Abstract: This paper presents the development of a generic framework for asset maintenance management. The framework has been presented in the form of an $IDEF_0$ process model. The process model served to illustrate the interaction and dependencies among diverse set of knowledge areas. In this framework, outputs from one management process become inputs to another in a subsequent hierarchy. The structure of the framework model exhibited the characteristics of flexibility and robustness. Updates in knowledge can be accommodated within the framework through incorporating new management processes and/or activities, as well as establishing new sequencing logic for these processes and/or activities. In a supporting effort to the development of the framework model, the authors have objectively reviewed the general capabilities of three commercially available software applications that are known within the asset management (AM) industry. These three applications while encompassing wide selection of capabilities, represent a typical selection of information technology (IT) tools and techniques that are widely used in strategic asset management practices. The objective of this review is to study the operational characteristics, functionalities and to assess the capability of software interoperability of a representative sample of IT tools known within the AM industry.

INTRODUCTION

Any constructed facility can be considered as an asset or an investment that needs to be maintained to ensure its optimal value over its life cycle. Municipal infrastructure systems consist of many different types of assets that could have life spans beyond 50 years. Building systems, such as roofing, mechanical, or electrical systems, usually have a shorter life span than their supporting structures. These systems are in constant need of regular maintenance to ensure that they continue to function properly and that they retain their value and good appearance. Maintenance, as per British Standard 3811, is defined as "the combination of all technical and administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function" (Glossary 1984).

The field of AM is becoming increasingly professionalized. Operational knowledge for the practice of AM was found to exist within literature, current software, and current practice. However, this body of knowledge appears to be less well developed than areas

[1] NSERC Post-Doctoral Res. Fellow, Inst. for Res. in Constr., Nat. Res. Council Canada, Ottawa, ON, Canada, K1A 0R6, E-mail: mohammad.hassanain@nrc.ca
[2] Assoc. Prof., Dept. of Civ. Engrg, Univ. of British Columbia, Vancouver, BC, Canada, V6T 1Z4, E-mail: tfroese@civil.ubc.ca, URL: http://www.civil.ubc.ca/~tfroese/
[3] Sr. Res. Ofcr., Inst. for Res. in Constr., Nat. Res. Council Canada, Ottawa, ON, Canada, K1A 0R6, E-mail: dana.vanier@nrc.ca

such project and construction management (e.g., as observed by the relative number and range of books and scholarly literature in these areas). Some efforts were found to formalize AM knowledge and practice in models, but these were found to be few and partial in their coverage of the breadth and depth of AM concerns.

The challenge for this paper was to synthesize the available knowledge sources into a formal model for the practice of maintenance management. The primary motivation for this research was the development of Information Technology (IT) solutions for AM, but the resulting process model also offers other benefits in structuring the organization and management of AM knowledge and AM operations.

Asset management is currently a young and growing, yet still a fragmented industry. One of the contributing factors to this fragmentation is that the asset management industry is witnessing a proliferation of software tools (Vanier 2001). Furthermore, each of these software tools is providing standalone solutions to a multitude of problem areas, such as asset inventory, condition assessment and strategic planning. As a result, there exist many data format and databases, leading to pools of unstructured data (Kyle et al. 2000; Peters and Meissner 1995) with poor interoperability. Moreover, no software solutions were found that have the potential to integrate data throughout the full cycle of asset management (AM).

The objective of this paper is to present a framework model, which aims at being a systematic and generic reference to the practice of maintenance management for constructed assets. With this objective in mind, the authors reviewed three available commercial software packages that are currently used within the AM domain, by studying their operating characteristics and functionalities. The advantages and disadvantages of the software related to the practice of maintenance management are identified and discussed. A framework model is presented, described and critiqued.

The development of the framework model constitutes an effort to standardize business processes, the activities that need to be undertaken and the methodology of how and what information needs to be communicated between processes. The framework model can then be used in practice and implement in software.

MAINTENANCE MANAGEMENT SOFTWARE REVIEW

This section objectively reviews the general capabilities of three commercially available applications that are known within the AM industry. These three applications while encompassing wide selection of capabilities, represent a typical selection of IT tools and techniques used in strategic asset management. The objective of this software review is to study the operational characteristics, functionalities and to assess the capability of software interoperability of a representative sample of IT tools. The first application is BUILDER and its focus is condition assessment and maintenance planning. The second application, MAXIMO, is an integrated system dealing with a wide spectrum of activities, but primarily for buried infrastructure. The last application evaluated is

RECAPP which focuses on inventory identification, condition assessment and maintenance planning.

BUILDER from U.S. Army

BUILDER, Version 1.1, developed by the US Army Construction Engineering Research Laboratories (www.cecer.army.mil), provides capabilities for inventory collection, condition assessment information collection on buildings and maintenance/repair analysis. A sister application developed by the Army called MicroPAVER is well-known for the maintenance management of roads and airfields (Shahin, 1992). These applications are from of a suite of programs called Engineered Management Systems (EMS).

The inventory capability within the BUILDER allows storage and retrieval of general information on buildings, where each building is divided into twelve systems, including: roofing, site, specialties, structural, fire suppression, HVAC, interior construction, exterior construction, plumbing, conveying, electrical and exterior closure. Each of the twelve systems is divided into a number of components, and each component is further divided into an appropriate number of sections.

Based on the collected condition assessment information, BUILDER uses the Building Condition Index (BCI), which is derived from the System Condition Index (SCI), which is in turn derived from the Building Component Condition Index (BCCI), to provide a qualitative measure of the building, system and component's ability to perform its function. It involves inspecting each component of the above-listed systems visually, evaluating it against a set of pre-defined rating criteria, and selecting an appropriate rating. The condition rating procedure is a less accurate than that of MicroROOFER, but it presents a faster method for performing a condition survey.

The rating approach is based on employing three broad rating categories "Red", "Amber" and "Green", where "Red" implies serious problems, and that major maintenance and/or repair is need; "Amber" serves to caution that while things are generally adequate, maintenance and/or repair would make economic sense; "Green" implies that things are fine, although minor maintenance and/or repair may be needed. While the inspector determines which rating category to classify a component in, each rating category is further subdivided into three sub categories, donated as high (+), low (-), and middle for further refinement.

In order to define which maintenance and/or repair planning strategies to implement, BUILDER prompts the user to define standards and policies. An example of such standards is that the user can set requirements that the minimum Condition Index (CI) value to carry out a repair should not be less than 70 out of a possible 100, and that minimum ratio of repair cost to replacement cost to change repair to replace is 0.7. Out of these standards and policies, maintenance and/or repair activities can be prioritized according to three prioritization schemas: a complex default, a simple default, and a simple default with MDI. Maintenance and/or repair work items are then ranked according to the current condition indexes (CI), available funding, and Remaining Service Life (RSL). The user can then view the ranked listing of maintenance and/or repair work items along with the estimated cost for each, for a particular year. The user can then choose to follow BUILDER's recommendation on what work item to proceed with first, or to overwrite BUILDER's recommendation and to proceed with other work items.

MAXIMO from MRO

MAXIMO Enterprise (MAXIMO 2001), version 4.03, developed by MRO Software, Inc. (www.mro.cam), provides capabilities for inventory collection, condition monitoring, maintenance planning and scheduling, and procurement of machinery and components in plant facilities.

The inventory capability within the software allows storage and retrieval of general information on equipment assets. MAXIMO allows the specification of inspection techniques to be followed such as visual inspection or destructive testing through its Job Plan function. Its ability to use failure and problem codes that can be tied directly to work orders allows the recording of defects found in spaces or elements within the assets. Inspection results can be recorded on work orders. There is limited capability in the condition-monitoring module to determine the existing condition of an asset relative to pre-set performance requirements. However, it allows the user to generate a preventative maintenance plan and record failures and problems with components in order to generate a work order to rectify the condition of the asset.

The job planning functions of MAXIMO allow the estimating of the cost of labor, equipment and material needed to perform a maintenance/repair/renewal action. There does not appear to be capability of MAXIMO to specify the probability of asset failure, the consequences of asset failure, or the remaining service life if no maintenance/repair/renewal action was carried out.

The reporting capabilities within MAXIMO allow the set up and printing of maintenance work requests, including the identification of maintenance/repair/renewal backlog awaiting completion. While the reporting capability of MAXIMO is flexible, its usefulness is dependent on work order coding and use of status flags. Using MAXIMO's job plans, the user can specify various attributes related to the work being requested. These attributes include specifying work location, labor needed, material needed, equipment needed, and desired completion date. MAXIMO is a client-server application (relational database shell). It allows the capability to link CAD and text files to inventory items.

RECAPP from PPTI

RECAPP, Version 2001.0.0, developed by Physical Planning Technologies Inc. (www.recapp.com), is an application developed to provide capabilities for inventory collection, maintenance work order reporting and long-term budgeting. The user can install any one or many of the software modules, including the a report manager for allowing the user to chart graphics for various data; an administration module for controlling the overall look and feel of the dataset, the objects, and the data fields; a budget manager for displaying financial projections out to 25 years in the future; an event manager for reporting outstanding maintenance actions; or a scenario builder for creating "what ifs" scenarios regarding future budgets.

RECAPP permits the user to add any number and type of assets to its database. The user can customize a number of fields to express the attributes of the various levels of asset entities; for example, construction year, gross area, replacement value and asset type; replacement schedules for the technical components; and the estimated cost and time schedule, estimated cost and difficulty factor for the maintenance events.

Events can be created to schedule inspections, record their attributes, and hence reach a condition statement on the components being inspected. The user can also prioritize maintenance projects based on condition and budgetary constraints. The application allows the user to select which maintenance project will be approved for the appropriate implementation. RECAPP is a standalone application (relational database with object-oriented classes' structure). It allows the capability to link CAD and text files to inventory items at any level of abstractions (i.e. portfolio, buildings, sectors and technical components).

Summary

AM software tools such as those discussed in this paper provide both a repository for asset data and a process for data routing and data control. As can be clearly seen, the applications are different, despite the fact they all deal with AM: they save different data and they invoke different processes or different portions of the processes for their users. In fact, most, if not all, asset management applications are similar to the three tools discussed. The science of maintenance management is evolving, almost as a result of the rapid adoption of information technologies. There are new requirements for data structures as well as process models. Based on the authors' experiences with asset management tools, a generalized maintenance management framework model is proposed to the user community. It forms the process required to perform maintenance management, and as such also identified data requirements for the maintenance management industry.

GENERIC MAINTENANCE MANAGEMENT FRAMEWORK MODEL

This section presents the development of an integrated framework model for maintenance management of built-assets (Hassanain 2002). Development of this framework was motivated by the desire to develop IT solutions for the AM industry. However, the framework is useful beyond its role in supporting IT. The framework, presented as a process model, is generic, meaning that the activities involved can be applied to non-specific assets, rather than to a specific asset type in a facility (for example, the framework can be applied to systems such as roads, bridges, buried utilities, or buildings.). Further, the framework can be applied at both the level of individual projects or on a network of projects. The framework can also be used to analyze current maintenance management practices in AM organizations, regardless of whether the tasks involved are implemented by in-house staff or professional maintenance contractors.

The framework model is unique in that it describes a collection of diverse knowledge areas that have been analyzed for the AM domain in a formalized and standardized view. The framework model consists of five sequential processes. For each of the processes, a number of supporting activities have been defined, with their logical sequence and information requirements. A detailed description of the processes and the functions within is provided below. It should be noted that, while every maintenance project is likely to be unique, some of the identified functions within each process can be omitted depending on the characteristics of the asset being examined. The five processes forming the framework model are as follows:

1. Identify Assets (referred to as node "A")
2. Identify Performance Requirements (referred to as node "R")
3. Assess Performance (referred to as node "P")
4. Plan Maintenance (referred to as node "M")
5. Manage Maintenance Operations (refereed to as node "O")

The generic framework is described schematically as an $IDEF_0$ (Integration Definition for Function Modeling) process model diagram, as shown in Fig. 1. A process model describes the activities that exist within a business process. It defines the tasks that need to be undertaken within each process, and illustrates how and what information needs to be communicated between tasks (Federal 1993). In $IDEF_0$ notation, boxes represent tasks while arrows from the left, right, top and bottom represent inputs, outputs, controls and mechanisms, respectively. The process model served to illustrate the interaction and dependencies among diverse set of knowledge areas. Outputs from one management process become inputs to another in a subsequent hierarchy. The structure of the framework exhibited the characteristics of flexibility and robustness. Updates in knowledge can be accommodated through incorporating new management processes and/or activities, as well as establishing new sequencing logic for these processes and/or activities. A series of interrelated diagrams illustrating information flow from one activity to another, at different levels of detail, are presented throughout this paper.

The "Identify Assets" Model

Process Definition

The "Identify Assets" process (node "A" as shown in Fig. 1) involves carrying out an inventory activity to identify the assets that may require maintenance operations within their service life. An asset may be defined as a uniquely identifiable element or group of elements which has a financial value and against which maintenance actions are recorded (IAI 1999). Service life may be defined as the actual period of time during which the asset, or any of its components, performs without unforeseen costs of disruption for maintenance and repair (CSA 1995). The inputs necessary to carry out the "Identify Asset" process are: an already existing asset and a set of resources, as displayed by the input arrows in node “A” in Fig. 2. The output is a list of assets requiring maintenance. This process is broken down into three functions as shown in Fig. 2. The following paragraphs provide a description of the functions involved.

Process Activities

Identify Assets for Evaluation (A.1): Serves to identify the assets (against which maintenance, repaired or renewal activities are carried out). Data identified in the asset register may include asset name, identifier, location, expected life, original value, current value, depreciated value, total replacement value, incorporation date, commissioning date, and warranty duration from manufacturer (IAI 2000).

Select Products to Treat as Assets (A.2): Serves to identify the specific products that may undergo maintenance work, hence treated as assets for the purpose of evaluating their need for maintenance, repair or renewal activities, in an asset management information system.

Compile Inventory of Assets (A.3): Serves to compile a record of the identified assets in an asset management information system for the purpose of identifying their performance requirements, assessing their current condition against a pre-determined set of performance requirements, identifying the specific maintenance, repair or renewal activities that needs to be carried out, and developing schedules for performing these activities. These assets are not yet evaluated at the time of compiling the inventory list.

The “Identify Performance Requirements” Model

Process Definition

The “Identify Performance Requirements” process (node “R” as shown in Fig. 1) includes functions required to identify categories of performance requirements of an asset as a unified entity (e.g. road, bridge, trunk sewer), as well as the components that make-up the assembly of the asset. Performance may be defined as the behavior of a product related to use (ISO-6241 1984). The scope in this process also extends to identifying performance indicators and their means of expression within each category of performance requirements. Within this process, performance requirements can be defined for whole asset and technical systems composing that asset. However, treating performance requirements on the level of whole asset, rather than the level of individual technical systems, satisfies the concept of total asset performance. Literature (Hartkopf et al. 1986) revealed that although a building system may provide adequate performance in one dimension, it might fail in other area due to specification or context. Therefore, care should be taken not to identify the various measurements with individual technical systems and assemblies (in isolation), such as road surface, or manhole, since it is usually the interactions of these systems or assemblies that fail. The input to this process is a list of assets requiring maintenance, which are obtained from asset registers. The outputs are statements of the performance requirements as well as a range of acceptable performance values. This process is broken down into five functions as shown in Fig. 3. The following paragraphs provide a description of the functions involved.

Process Activities

Verify Current Use of Asset (R.1): Serves to verify and/or analyze the current use of the asset and the occupancy conditions against those specified in specification documents, at the beginning of the commissioning phase. In this function, performance agents such as mechanical, electromagnetic, thermal, chemical and biological agents, which may impact the behavior of the asset may be identified according to their origin and nature. The origin of these agents may be either external to the asset and caused by environmental conditions around the asset; or internal to the asset and caused by loads and usage on the system. (ISO 1984).

Identify Performance Requirements of Asset (R.2): Serves to identify the performance requirements that the asset, as a unified entity, has to meet. A performance requirement may be defined as user requirement expressed in terms of the performance of the product (ISO 1984). In this function, performance requirements are defined without imposing constraints on the form or materials of the solutions proposed to fulfill these requirements. The most representative categories of performance requirements in agreement with a number of references on the concept of total asset performance (ISO1984, ISO1992, Hartkopf et al. 1986, Blachere 1993) include: durability, fire safety, acoustical quality, thermal quality and lighting requirements in the buildings domain and road condition index (Shahin 1992).

Identify Performance Requirements of Asset Components (R.3): This function runs in parallel with function R.2. It should be considered when the performance of a specific asset component is in question. It serves to identify the performance requirements that the asset components (e.g. technical systems) have to meet. In the case of low-slope conventional roofing systems, for example, groups of performance requirements were described to include: water tightness, energy control, condensation control, air leakage control, load accommodation and maintainability (Lounis et al. 1998a).

Identify Performance Indicators (R.4): Serves to identify the parameters adequate to measure all aspects of performance in performance categories. Analysis of the literature indicated that the diversity of performance requirement categories of assets and/or components defies the definition of a *single* parameter which is adequate to measure all aspects of performance. Hence, to judge performance effectively, each category of performance is considered separately. For example, while some of indicators of the durability requirement category include the existence of deflections, cracks and corrosion, some of that of the fire safety requirement category include duration of evacuation time, survival time, provisions of smoke detectors and exist signs.

Identify Performance Values (R.5): This serves to state the upper and lower limits of acceptable performance values, hence providing a range of acceptable solutions to fulfill the performance requirements. While international standards may specify performance categories for particular assets and components, specification of performance values is the task of designers (ISO-7361 1986). Each performance requirement has a “comfort zone” that establishes the limits of acceptability for the user or asset manager.

The "Assess Performance" Model

Process Definition

The "Assess Performance" process (node "P" as shown in Fig. 1) includes functions required to assess the condition of an asset, and determine the deviation in the performance, which occurred through its service life. It involves identifying the performance assessment method(s) and their pre-set frequencies, depending on the configuration of the asset being examined. The objective of this process is to catalog assets and/or components that have ceased to meet the performance requirements specified in process R and, hence, require a maintenance, repair, renewal action. Maintenance includes general activities such as cleaning manholes, removing sand from roads, and replenishing depleted protection fluids in mechanical equipment. Repair includes unplanned intervention activities, performed to rectify situations of distresses found. Renewal includes activities to install a new asset and/or component to replace the one in-place, due to economic, obsolescent, modernization or compatibility reasons (Vanier 2000). . There is always the "Do nothing" options which includes postponing or ignoring maintenance, repair or renewal. In the "Assess Performance" process, a condition assessment survey of an asset relies on counting visible defects. While this method may be appropriate for accessible and easy to observe systems such roadways, other systems such as buried utilities, road subgrade, or concrete reinforcement may be difficult to access and observe. This, in turn, necessitates looking for clues such as spalling, potholes, water stains, and unusual noises to ascertain condition (Uzarski 1999). The inputs to this function are statements of acceptable performance values from process R. The outputs are statements of the asset condition and a range of management options that objectively specify a set of actions when a specific set of conditions occurs. This process is broken down into four functions as shown in Fig. 4. The following paragraphs provide a description of the functions involved.

Process Activities

Identify Condition Assessment Technique (P.1): This function shown in Fig. 4 identifies the condition assessment technique used to assess the performance of an asset and/or its components. Condition Assessment Surveys (CAS) may vary from being simple, visual walk-through, to thorough analysis that may include in-depth review of background documentation, in-situ and laboratory testing and disassembly of selected components (Cole and Waltz 1995).

Assess Asset Condition (P.2): This function is the core function of the "Assess Performance" process. All other functions within this process exist to support this primary function.

Identify Distress (Anomaly) (P.3): Serves to identify the distress or anomaly found in the asset through the CAS. Identifying distresses is achieved through carrying out particular functions, depending on the type of asset being assessed. This function is broken down into 4 sub-functions as shown in Fig. 5. The following paragraphs provide a description of the functions involved.

- **Identify Distress (Anomaly) Type (P.31):** Serves to describe the type of the distress found.

- **Identify Distress Severity Level (P.32):** Serves to describe the severity level of the distress found. Severity levels might range from low, medium to high.

- **Measure Quantity of Distress (P.33):** quantities are measured as number of units, or combined length, or areas of distress, depending on the type of the distress found.

- **Document Distress Cause(s) (P.34):** causes might range from an aggressive environment, inadequate design, poor workmanship to lack of maintenance.

Identify Management Options (P.4): Serves to describe the range of management options available when specific sets of conditions occur or are imminent to occur. The management options shown in Fig. 4 include carrying out one or a combination of the following: maintenance, repair, renewal or doing nothing. An input to this function is a statement on the condition of the asset being examined. A review of literature indicates that asset conditions may be expressed either quantitatively, as a numerical rating (i.e. condition index), or qualitatively as a categorical rating.

The "Plan Maintenance" Model

Process Definition

The "Plan Maintenance" process (node "M" as shown in Fig. 1 and detailed in Figs. 6 and 7) includes functions that are required to determine maintenance priorities based on three identified conflicting management objectives as one of the methods involved in planning maintenance. While these objectives were identified in the context of a specific asset (Lounis et al. 1998b), the authors believe that analysis of the same set of objectives is valid for non-specific assets. These objectives are:

1. Minimizing maintenance cost: This objective is treated through performing a life cycle costing analysis to predict initial and future expenditures associated with a maintenance, repair or renewal operation over the life cycle of an asset.
2. Maximizing asset performance: This objective is treated through predicting the performance of an asset for each of the different maintenance options. One method of performance prediction of assets is based on the principles of Markov chain, which determines the deterioration in condition through a series of algorithms using Markovian probability matrices and condition states (Lounis et al. 1998b).
3. Minimizing risk of failure: This objective is treated through concurrently considering the probability of failure and the consequences of failure. One method to calculate the probability of failure is obtained through the Markovian model. A consequence of failure is a statement of cost figures associated with loss of productive time and damage to surroundings (Lounis et al. 1998b) or damage to other systems that could in turn exacerbate damage.

The inputs to this process are statements of the asset condition and its components, as well as a set of management options to be implemented when a specific set of conditions occur or are about to occur. The output is an optimal decision or a strategy based on the result of the analyses carried out within this process. This optimal decision is translated into identifying maintenance workload to proceed, and as a result, a maintenance work order is issued so that maintenance jobs would be implemented. Another output of this process is a list of deferred maintenance jobs, which are of secondary priority and are awaiting funding. This process is broken down into five functions as shown in Fig. 6. The following paragraphs provide a description of the functions involved.

It is worth mentioning that while maintenance and/or repair prioritization strategies of an asset may be determined by a Multiobjective optimization approach, as per this paper, other approaches to plan maintenance and/or repair prioritization strategies also exist. These include safety, health, or environmental concerns prioritization, expert knowledge, and age-based prioritization.

Process Activities

Predict Remaining Service Life (M.1): Serves to perform an analysis to predict the performance and the service life of an asset.

Estimate Cost of Maintenance (M.2): Serves to estimate the resources required to carry out the maintenance work requested. This function is broken down into 4 sub-functions as shown in Fig. 7. The following paragraphs provide a description of the functions involved.

- **Estimate Number and Trade of Workers (M.21):** Serves to estimate the number and the trade of workers needed to perform the maintenance work requested. Some maintenance jobs require a crew of a single trade. Some jobs require multiple crews of multiple trades.

- **Estimate Number and Type of Equipment (M.22):** Serves to estimate the number and type of equipment needed to execute the maintenance work. The number of hours the equipment is going to be used can be estimated. The hourly rate for using the equipment can be determined.

- **Estimate Quantity and Type of Materials (M.23):** Serves to estimate the quantities and the type of material needed to perform a requested maintenance work. Some maintenance jobs are simple and require only one type of material. Some jobs are complex and require the combination of several materials.

- **Determine Total Cost of Maintenance Activity (M.24):** Serves to estimate the total cost of carrying out the requested maintenance job. The estimated cost would be the summation of the following cost items: man-hours, equipment/tools, and materials needed to perform the work.

Perform Multi-objective Decision Analysis (M.3): Serves to perform a risk-based multi-objective decision analysis to recommend a decision taking into consideration conflicting management objectives. These objectives are: minimization of maintenance and repair costs, maximization of the asset performance and minimization of risk of failure.

Identify Maintenance Workload to proceed (M.4): Serves to identify first priority maintenance jobs to be carried out based on the results obtained from the above-mentioned analyses.

Identify Deferred Maintenance Workload (M.5): Serves to identify the remaining maintenance, repair or renewal jobs, which have been deferred due to lack of funds in annual budget cycles, and for being of less priority, that should be carried out after the completion of the first priority jobs.

The "Manage Maintenance Operations" Model

Process Definition

The "Manage Maintenance Operations" process (node "O" as shown in Fig. 1) includes functions that are required to support the execution of maintenance operations and the implementation of maintenance, repair or renewal activities. The inputs necessary to carry out this process are a list of maintenance workload awaiting completion and a set of resources. The output is an operational facility. This process is broken down into five functions as shown in Fig. 8. The following paragraphs provide a description of the functions involved.

Process Activities

File Maintenance Work Order (O.1): Serves to communicate the need for carrying out maintenance work to the operations staff. The communication takes the form of a maintenance work order. Filing work orders provide the basis for planning, scheduling and effectively tracking maintenance workload. This function is broken down into 6 sub-functions as shown in Fig. 9. The following paragraphs provide a description of the typical tasks associated with filing and processing a maintenance work order. Each of these tasks is defined below.

- **Define Exact Problem (O.11):** Serves to describe the failure or defect in an asset that calls for a maintenance action to restore it to its original condition.
- **Define Location of Problem (O.12):** Serves to specify the location where the problem exists.
- **Identify Contact Person (O.13):** Serves to define the information of the person requesting the maintenance action to be carried out.
- **Note Request Date (O.14):** Serves to note the date for which the call for a maintenance action is requested.

- **Define Resource Type (O.15):** Serves to describe the type of resource needed to perform the maintenance work. Resources can be manpower, equipment and special tools required to perform the work.

- **Determine Quantity of Work (O.16):** Serves to determine the quantity of maintenance work, based on the extent of the defect described in the work order.

Plan Maintenance Activities (O.2): includes functions required to plan maintenance activities, and the method followed to achieve them. In essence, it involves setting up a work plan, for which questions like what, who, where, when and how the operational staff in an asset management organization will respond to a filed work order. The input to this function is a list of maintenance jobs awaiting completion. The output is a maintenance work plan. It should be noted that every maintenance project is likely to be unique, meaning that some of the functions within this process can be overlooked depending on the characteristics of the asset undergoing maintenance. This function is broken down into 5 sub-functions as shown in Fig. 10. The following paragraphs provide a description of the functions involved.

- **Choose Maintenance Work Method (O.21):** Serves to identify the method to be followed in performing the maintenance work. The choice of a specific maintenance work method over others will directly influence the cost and the duration of the maintenance work carried out.

- **Define Maintenance Activities (O.22):** involves defining a series of maintenance activities through the description of the given problem in the work order and the chosen work method to perform the work. This function is broken down into 3 sub-functions as shown in Fig. 11. The following paragraphs provide a description of the functions involved.

    - **Define Repetitive Activities (O.221):** Serves to list/outline the activities that would be carried out more than once as a result of processing a single work order. One example to illustrate this function would be having to crack seal the road surface at various locations in a network.

    - **Define Unique Activities (O.222):** Serves to list/outline the activities that would be carried out only once as a result of processing a single work order. One example to illustrate this function would be repairing a specific culvert.

    - **Define Lower-Level Activities (O.223):** Serves to define implicit activities when performing a maintenance activity. For example, painting work would be the general description in a requested work order (either repetitive or unique). To be able to perform this task, certain sub-tasks have to be carried out in process (lower-level activities), such as removing old paint, plastering wall surfaces, applying a sealer, a first coat of paint and then a second coat of paint.

- **Identify Precedence Relationship (O.23):** Serves to determine the logical sequence of the steps involved to carry out a requested maintenance work. This function is broken down into 3 sub-functions as shown in Fig. 12. The following paragraphs provide a description of the functions involved.

- **Define Starting Activity (O.231):** Serves to identify the first activity to start with in the process of carrying out a maintenance work.

- **Define Successor Activity (O.232):** Serves to identify the successor activities to the starting activities, and their sequencing logic.

- **Determine Lag between Activities (O.233):** this function involves defining the time between the completion of each activity and the start of the next.

- **Estimate Activity Duration (O.24):** Serves to estimate the time a maintenance activity takes be completed. The inputs to this function are information on estimated resources, productivity rates, sequencing logic, quantity of work, and location of work. Estimates of productivity rates for various asset maintenance and repair tasks can be obtained from published cost data such as RS Means Facilities Cost Data (1997). The output of this task is a maintenance plan.

Schedule Maintenance Activities (O.3): includes functions required to schedule maintenance activities. The inputs to this function are a list of maintenance activities, activity duration, estimated resources and sequencing logic. The output is a maintenance schedule. This function is broken down into 3 sub-functions as shown in Fig. 13. The following paragraphs provide a description of the functions involved.

- **Determine Activity to Proceed (O.31):** Serves to denote which maintenance work to proceed with.

- **Determine Work Date (O.32):** Serves to indicate the date for the commencement of the work.

- **Determine Activity Location (O.33):** Serves to give the location of the work.

Accomplish Maintenance Workload (O.4): includes functions involved in accomplishing the maintenance workload. The inputs to this function are sequencing logic, activity location, the activity to proceed with, and activity duration. The output is a completed maintenance workload. This function is broken down into 4 sub-functions as shown in Fig. 14. The following paragraphs provide a description of the functions involved.

- **Set Up Work Area (O.41):** Serves to establish and organize the work-space, depending on the complexity of the maintenance work requested.

- **Prepare Resources (O.42):** Serves to mobilize and coordinate the resources (manpower and equipment) needed to perform the work.

- **Perform Work (O.43):** this function is the core function of "Accomplish Maintenance Workload" model. All other functions within this process exist to support this primary function.

- **Clean Up Work Area (O.44):** Serves to denote the task of separating the waste products and removing them from the work space after the maintenance work is carried out. Partially consumed resources would also be salvaged for future use if needed.

Record Maintenance (O.5): includes functions required in recording accomplished maintenance work. These functions are usually noted by the crew that performed the work. The input to this function is a completed work unit. The output is an operational facility. This function is broken down into 4 sub-functions as shown in Fig. 15. The following paragraphs provide a description of the functions involved.

- **Report Completed Work (O.51):** Serves to report the completion of the work requested. In some circumstances, with the start of maintenance operation, the crew might discover much larger problems necessitating an increase to both man-hours and material quantity than originally estimated for. Such case of change of work scope prompts revising man-hour and materials estimate to reflect actual crew productivity and actual consumption of resources. Reporting completed work also serves to describe how well the maintenance work has been performed for quality control purposes.

- **Report Consumed Resources (O.52):** Serves to report the actual amount of resources consumed to accomplish a maintenance work order. This monitoring effort helps determine if the work has been accomplished at the lowest cost through examining manpower utilization, material usage and costs. Analysis of manpower utilization can be achieved through collecting data from all maintenance work orders on the number of man-hours and the quantity of material that each trade used to complete the work. Comparisons can then be made to determine the relative efficiency of current operations (Magee 1988). This function is broken down into 3 sub-functions as shown in Fig. 16. The following paragraphs provide a description of the functions involved.

    - **Report Number and Trade of Workers (O.521):** Serves to define the actual number and trade of crews who performed the work. This function also serves to compare the actual man-hours spent against the estimated man-hours.

    - **Report Type and Number of Equipment Used (O.522):** Serves to report the type and actual number of equipment needed to perform the work. This function also serves to compare the actual equipment-hours needed against the estimated equipment-hours.

    - **Report Type and Quantity of Material(s) Used (O.523):** Serves to report the type and actual quantity of material(s) needed to perform the work. This function also serves to compare the actual quantity of materials consumed against the estimated quantity.

- **Update As-built Drawings (O.53):** Serves to instruct asset management staff to update as-built drawings to reflect the changes, if any, to the configuration of the asset.

- **Report Actual Activity Duration (O.54):** Serves to report the actual time taken to perform the work. This function also serves to compare the actual duration of an activity against the estimated duration. This monitoring effort verifies that the assigned work crew is appropriate and the productivity rate is acceptable.

KNOWLEDGE FEEDBACK WITHIN THE FRAMEWORK MODEL

The $IDEF_0$ model illustrated in Figs. 1 though 16 shows the generic framework of maintenance management. They show that AM tasks are essentially sequential on a "per issue" basis. At any point in time, new information and thinking can cause the asset manager to go back to reconsider earlier work carried out in a preceding process. This creates opportunities for knowledge feedback with the maintenance management model. As a result, outputs from a succeeding management process become controls to the proceeding process. Controls are entities which influences or determine the process of converting inputs to outputs (Federal 1993).

It should be also noted that when considering the overall AM process, these tasks are being carried out over and over again, on a multitude of issues, at varying levels of detail; and any or all of these tasks may be going on at any given time. From this perspective, there can be a great deal of interdependency between the tasks. In particular, most of the information inputs to any of the tasks are based in some degree upon historical information, which comes about from the culmination of the output of previous cycles of the AM tasks. Although not displayed in Figure 1, it is implied that a feedback loop exists between any two succeeding and proceeding processes.

CONCLUSIONS

It has been shown in this paper that software to support AM industry does exist, but that it generally provides standalone solutions (that do not conform to an overall standardized framework) and each software program addresses one or more of a wide range of tasks throughout AM practice. This evolution of software has led to large volumes of independent, loosely structured data with poor interoperability.

This paper presents a generic framework for asset maintenance management. It describes a collection of knowledge areas within the domain of asset maintenance management. Although the knowledge areas described in the framework have previously existed in practice and documented in the literature, they have not yet been introduced to the asset management domain in a formalized and standardized view as presented through the development of the process model in this paper.

The framework can act as policy guidelines for the conduct of maintenance in an organization. It presents a solution to bridge the gaps in the practice of maintenance of built-assets by asset managers, such as implementing procedures for identifying performance requirements of assets and strategies for considering conflicting management objectives in decision-making. The framework also serves to standardize process descriptions, the activities that need to be undertaken, and the methodology of how and what information needs to be communicated between activities. The framework can also be used in the development of innovation software to address life cycle asset management.

The framework is schematically described as an $IDEF_0$ process model. Advantages gained from using $IDEF_0$ process models can be seen in the legibility exhibited in defining boundaries and responsibilities of functions within management processes, as well as the potential to improving the level of communication between the project's participants. Illustrating the framework in the form of $IDEF_0$ notation emphasizes the interaction and dependencies among knowledge areas. Outputs from one management process become inputs to another in a subsequent hierarchy. The structure of the framework becomes flexible and robust. Updates in knowledge can be accommodated through incorporating new management processes and/or activities, as well as establishing new sequencing logic for these processes and/or activities.

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APPENDIX. REFERENCES

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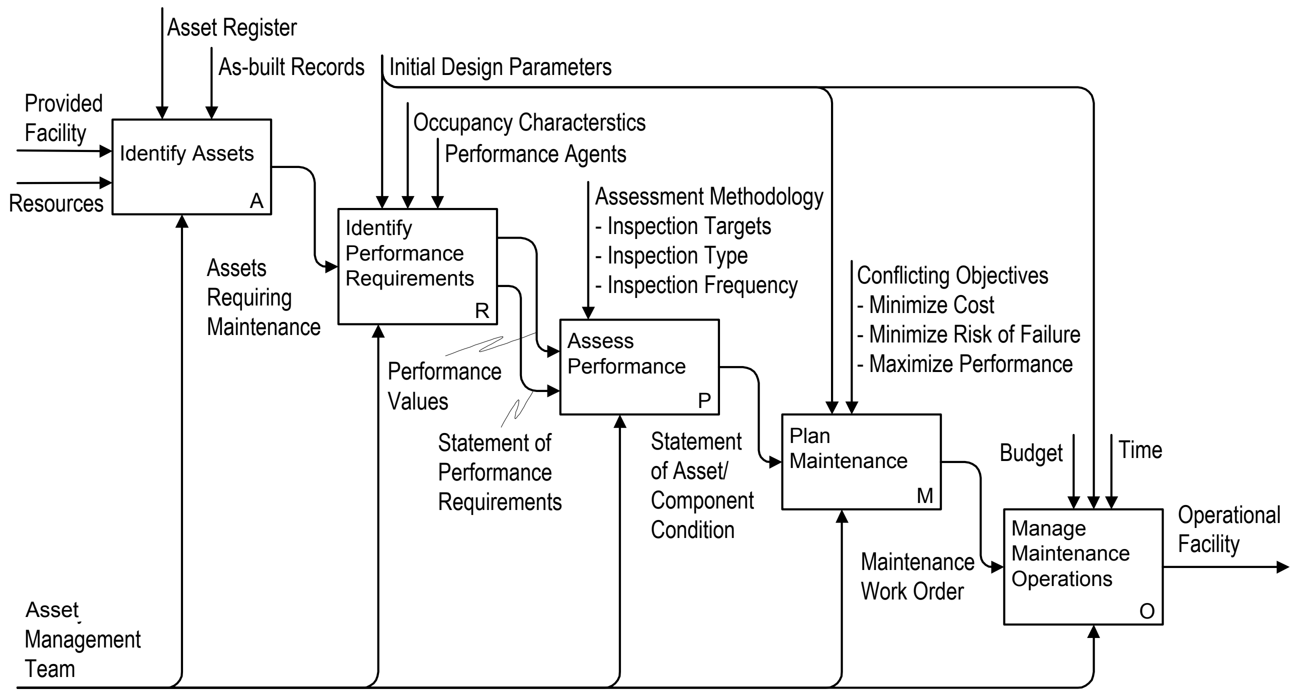

Figure 1: General processes involved in maintenance management model

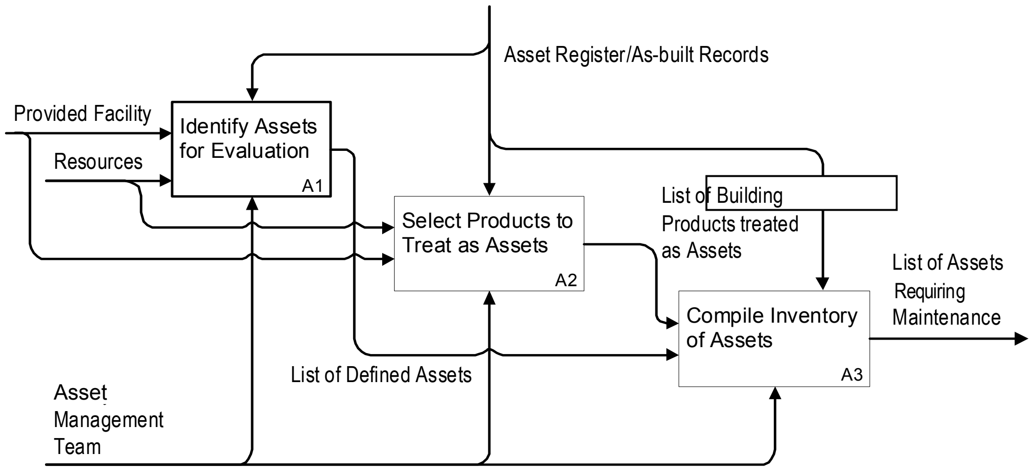

Figure 2: Node A, identify assets

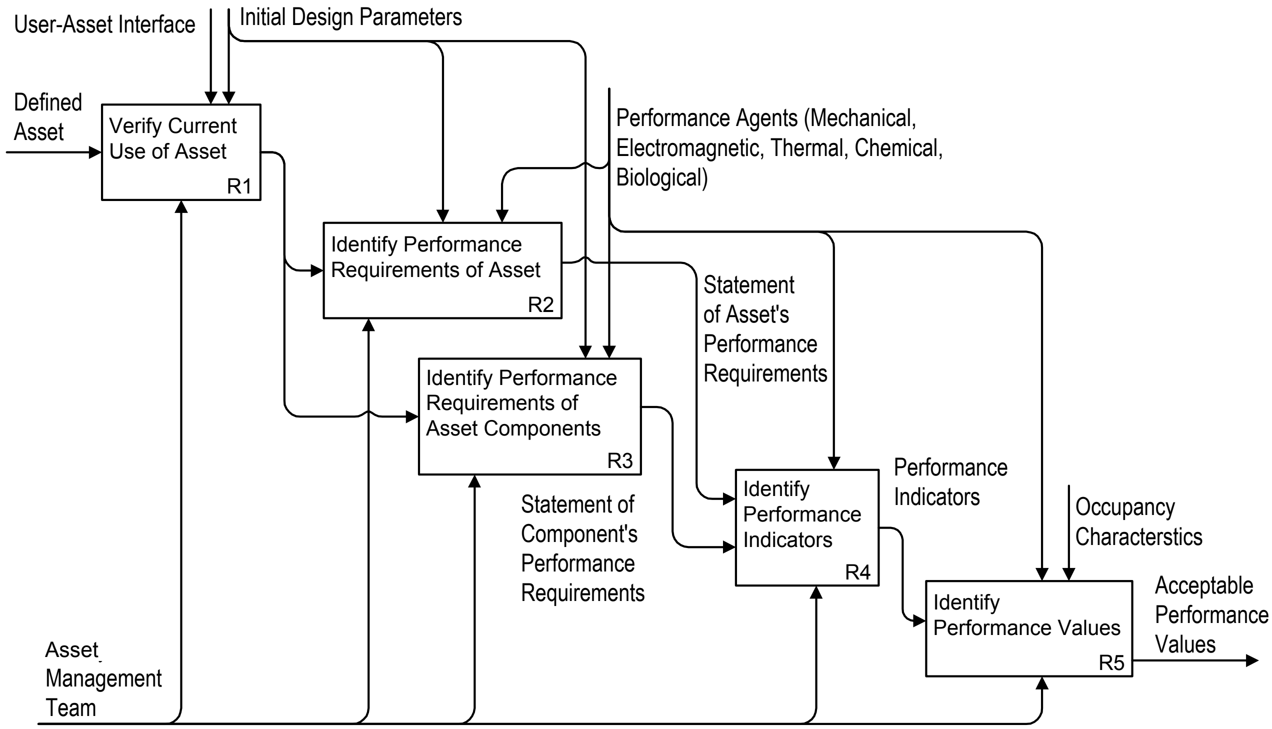

Figure 3: Node R, identify performance requirements

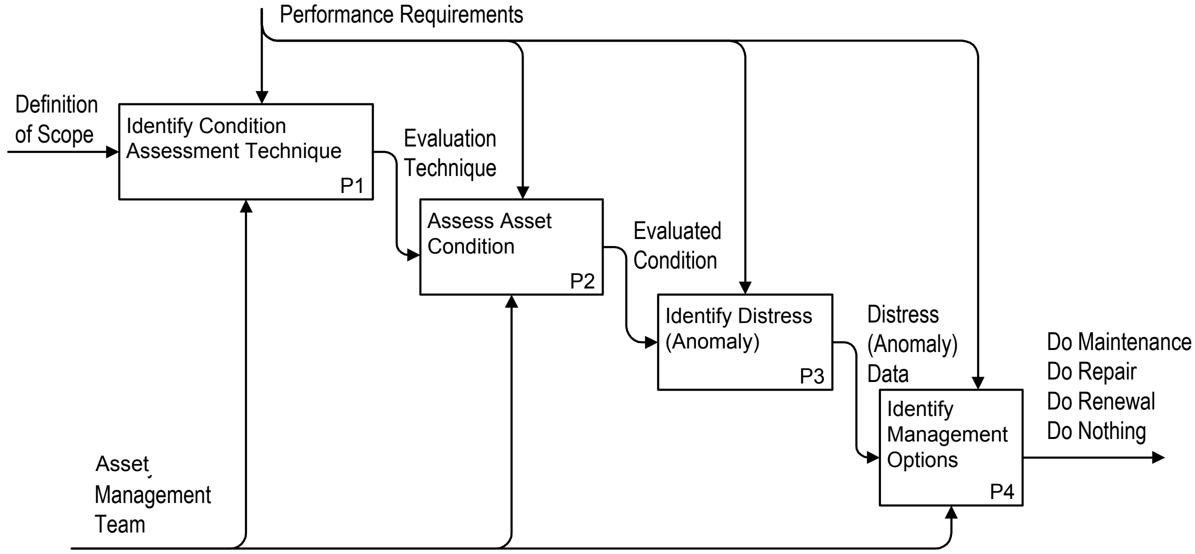

Figure 4: Node P, assess performance

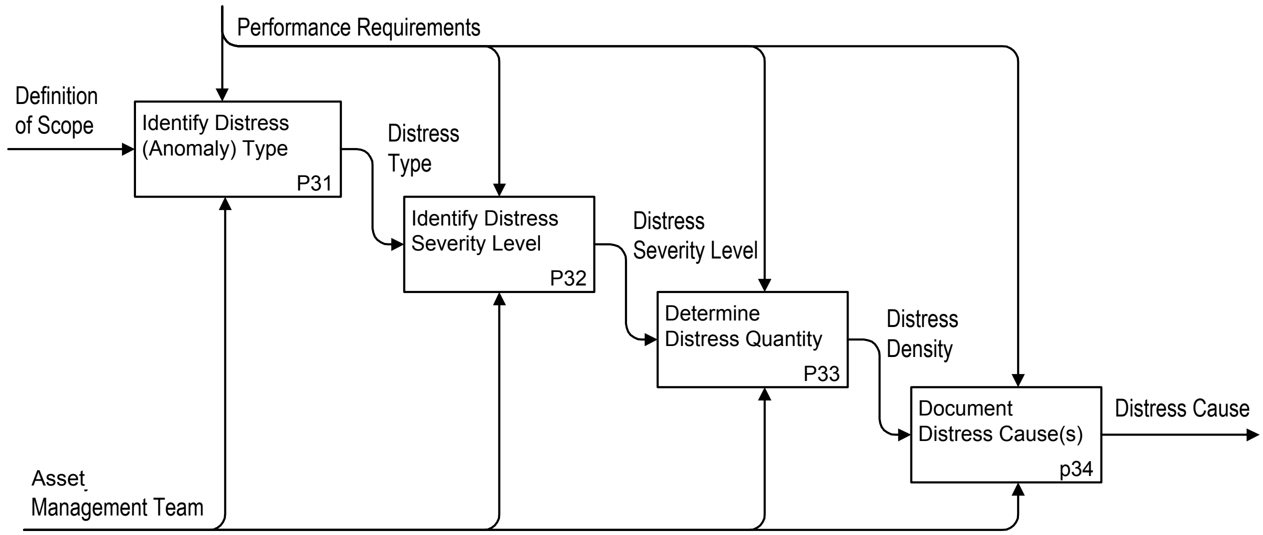

Figure 5: Node P.3, identify distress (anomaly)

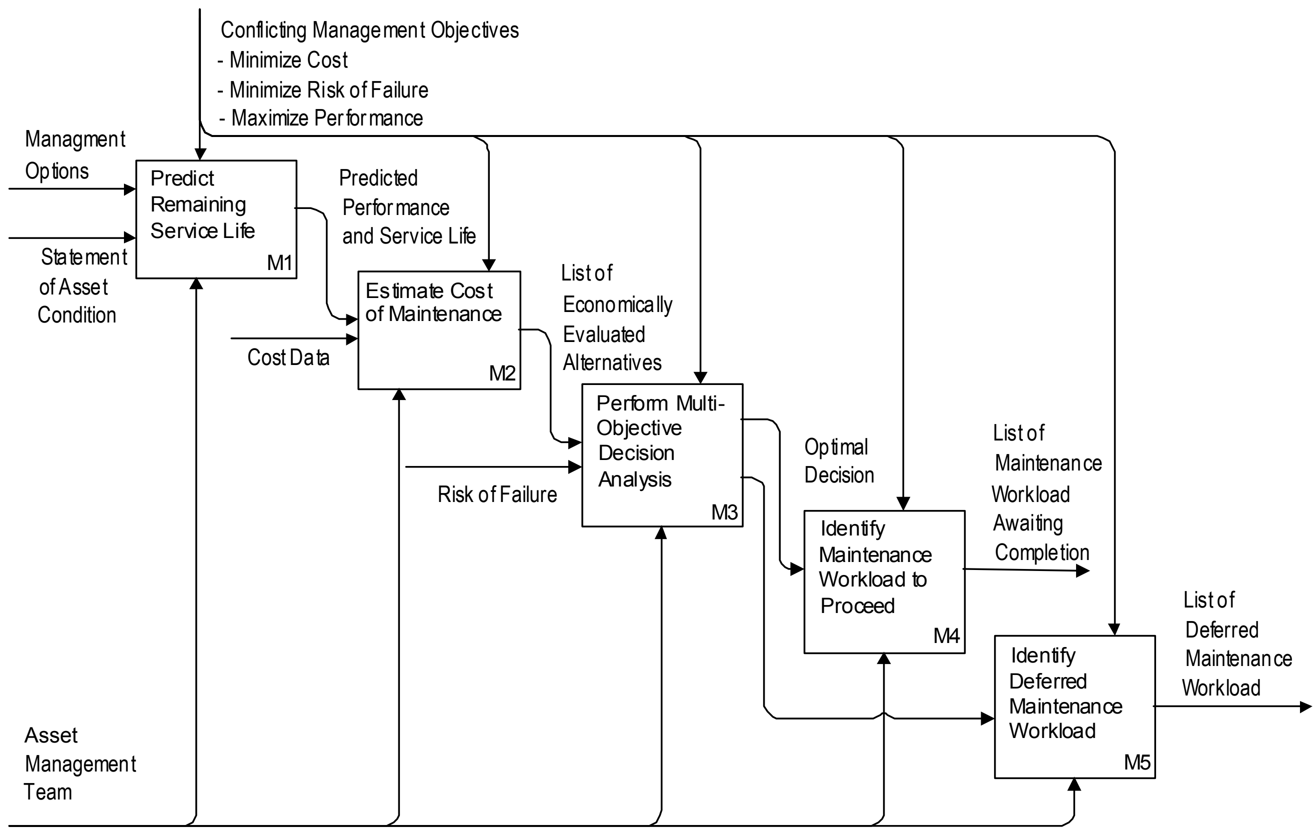

Figure 6: Node M, plan maintenance

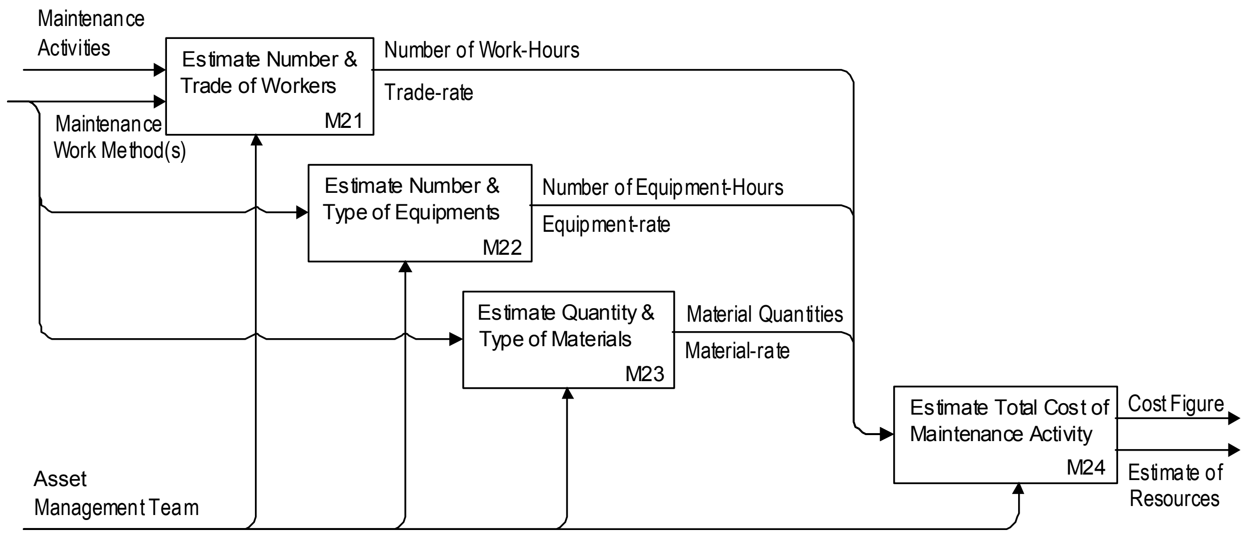

Figure 7: Node M.2, estimate cost of maintenance

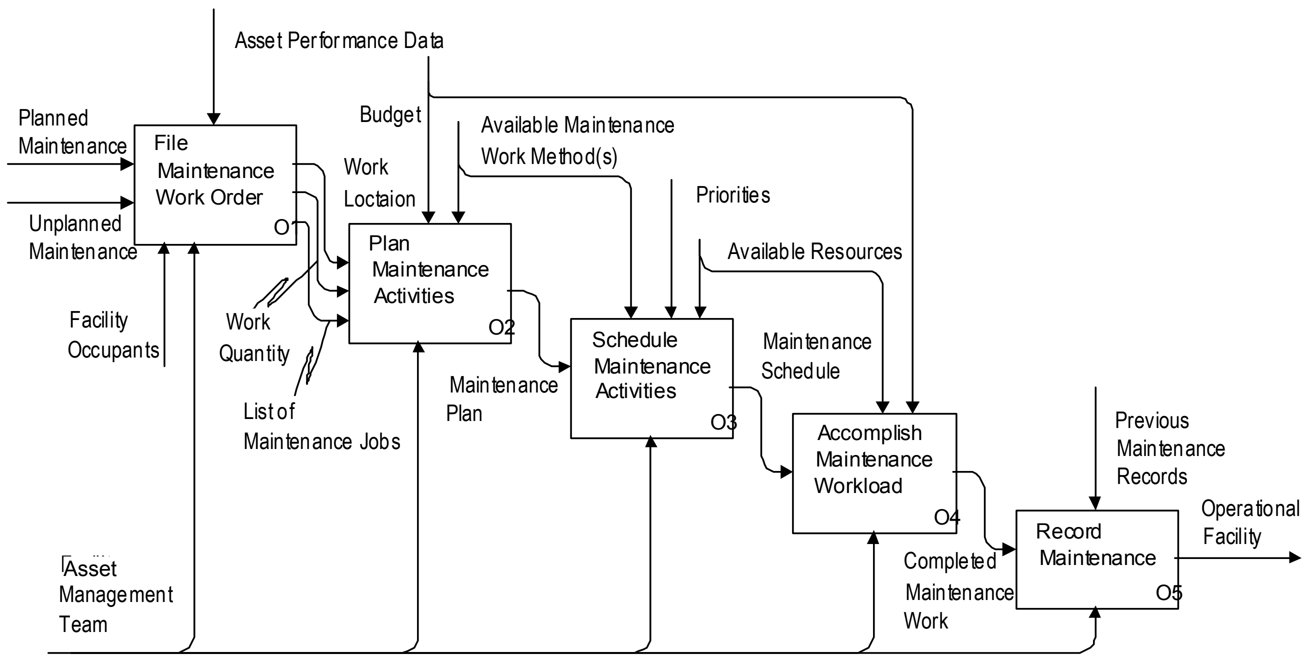

Figure 8: Node O, manage maintenance operations

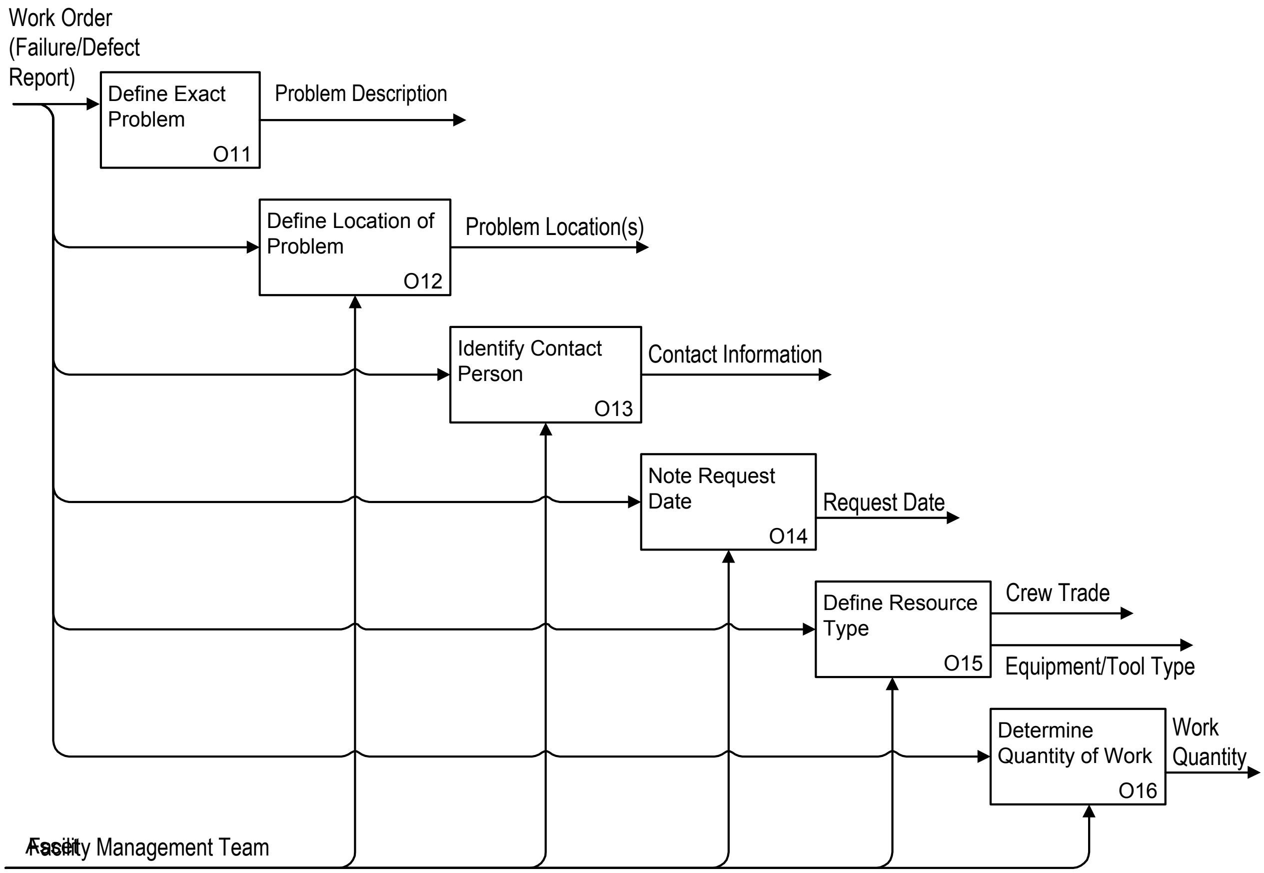

Figure 9: Node O.1, request maintenance work order

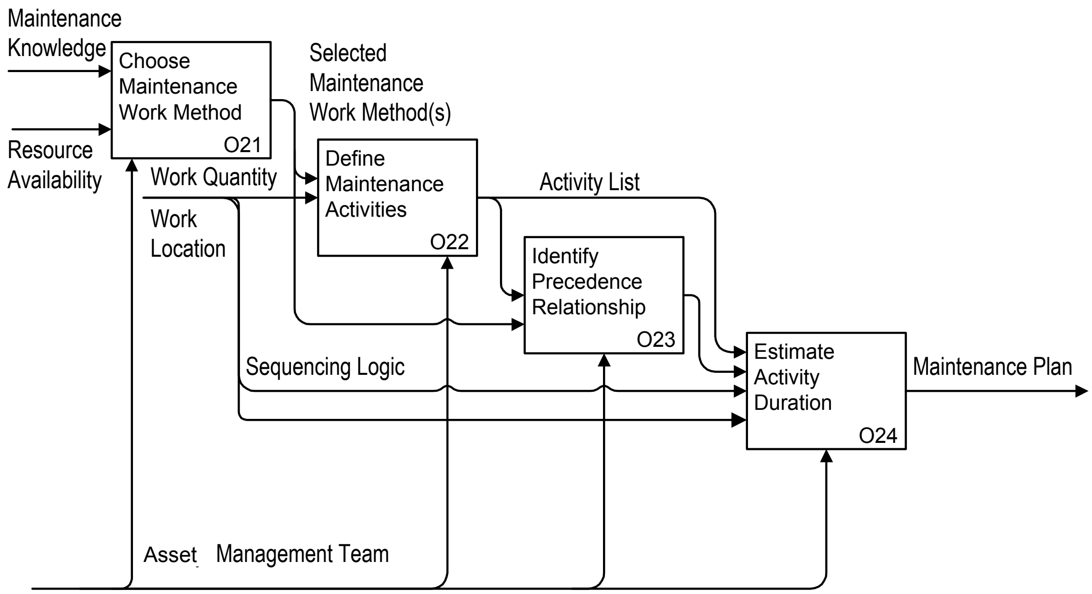

Figure 10: Node O.2, plan maintenance

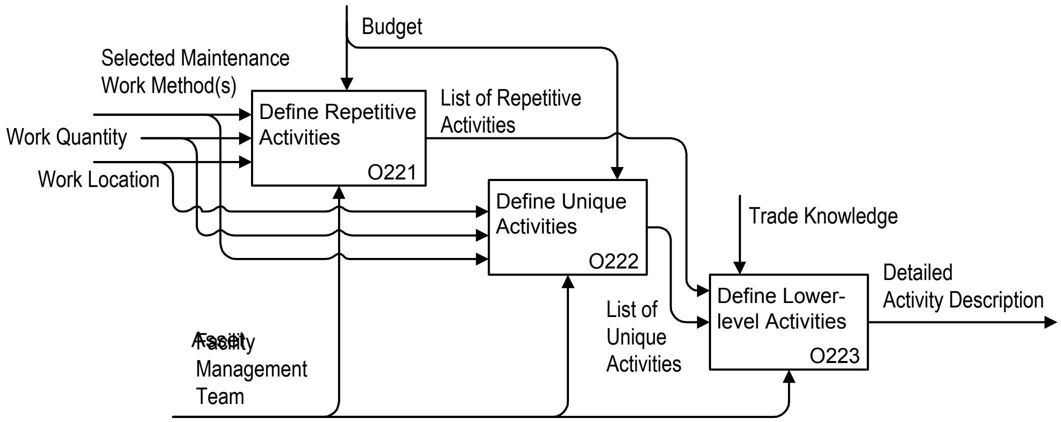

Figure 11: Node O.22, define maintenance activities

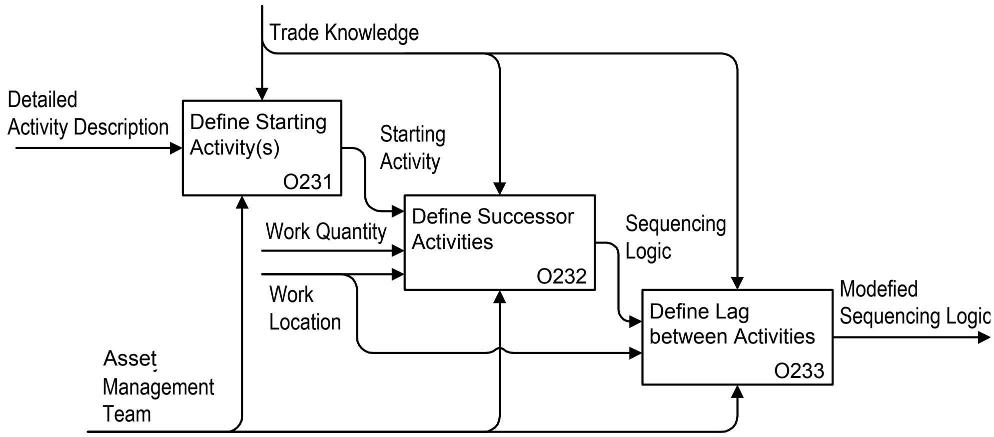

Figure 12: Node O.23, identify precedence relationship

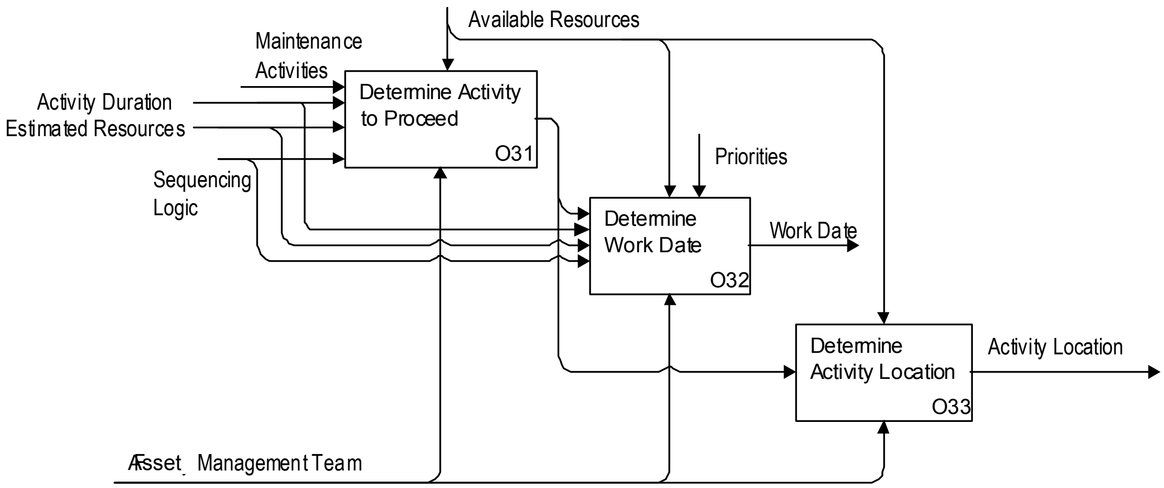

Figure 13: Node O.3, schedule maintenance activities

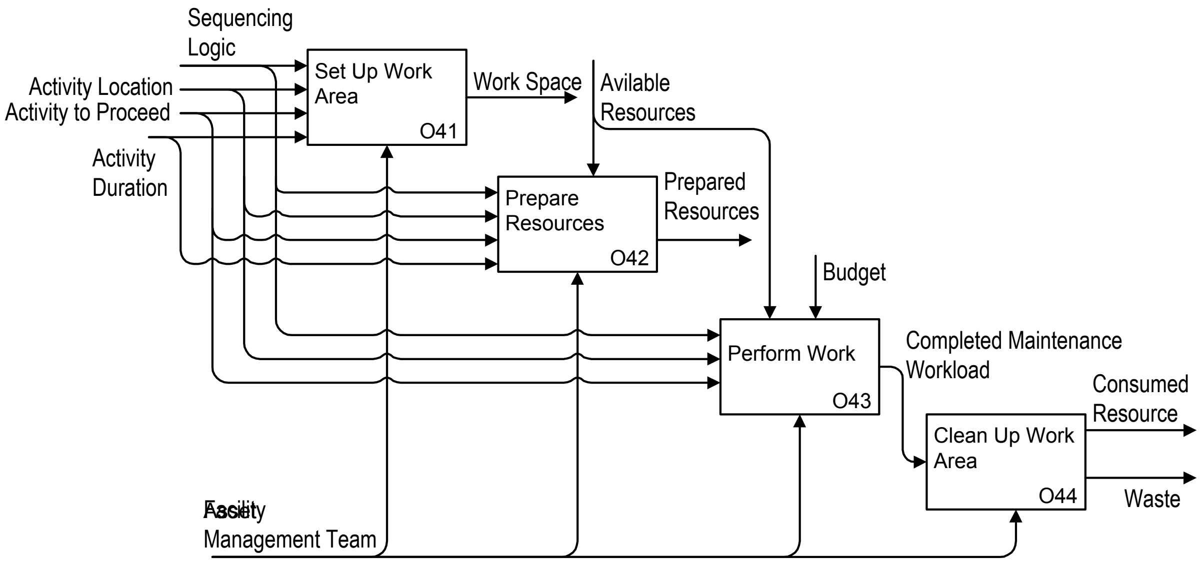

Figure 14: Node O.4, accomplish maintenance workload

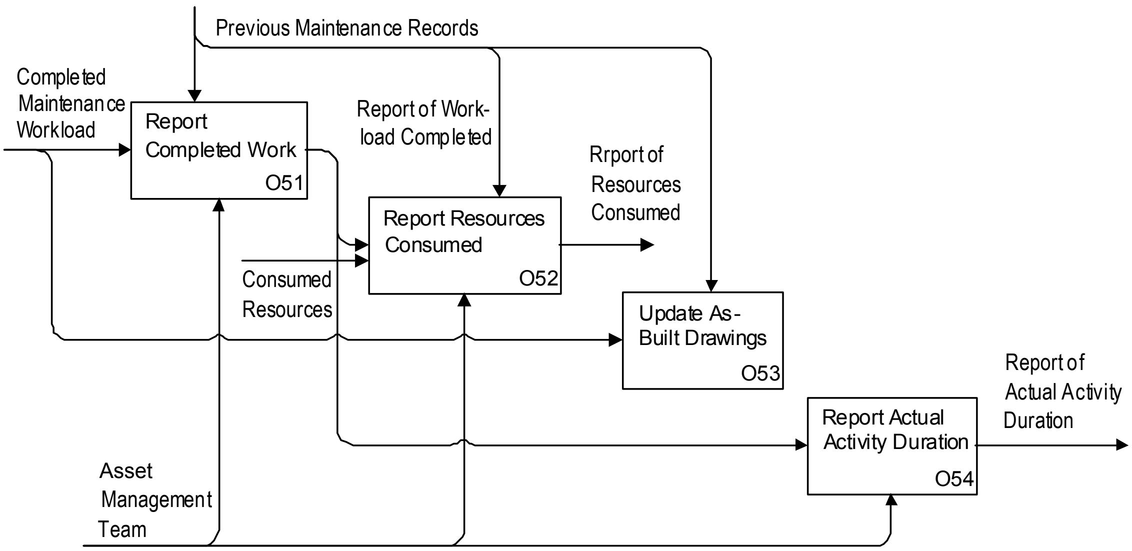

Figure 15: Node O.5, record maintenance

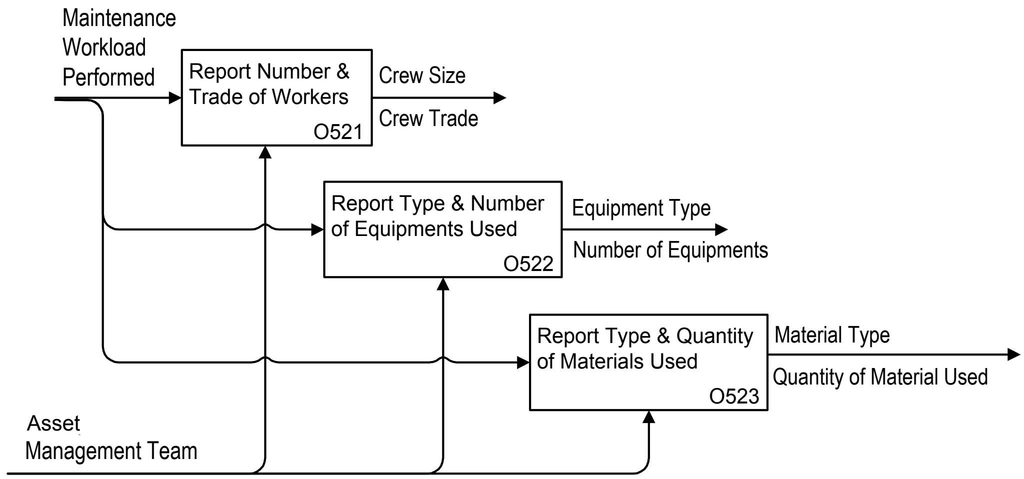

Figure 16: Node O. 52, report resources consumed