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Development of a maintenance management model based on IAI standards

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Abstract

This paper presents an object model for maintenance management of roofing systems as a case study to demonstrate the applicability of a proposed generic framework for integrating the maintenance management of built-assets. The framework consists of five sequential management processes: (1) Identify Asset, (2) Identify Performance Requirements, (3) Assess Performance, (4) Plan Maintenance, (5) Manage Maintenance Operations. The model builds upon the Industry Foundation Classes (IFCs) (Releases 2.0 and 2X) to define object requirements and relationships for the exchange and sharing of maintenance information between applications. Maintenance Management is one of the defined projects within the Facilities Management (FM) domain committee of the International Alliance for Interoperability (IAI). The paper proposes several extensions to the IFC's including the representation of functional requirements, assessed condition of objects, inspection and maintenance tasks, and libraries of non-specific information. Usage scenarios are provided to illustrate the use of the model to carry out selected processes.

Keywords: Maintenance Management; Data Standards; International Alliance for Interoperability; Industry Foundation Classes

1. Introduction

A building can be considered as an asset or an investment that needs to be maintained to ensure its optimal value over its life cycle. Building systems, such as roofing, mechanical, or electrical, usually have a much 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 original appearance. Maintenance, as per British Standard 3811 and this paper, 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"[8].

The asset management industry is witnessing a proliferation of information technology (IT) tools [26] each capable of providing solutions to a multitude of problem areas. This proliferation of IT tools is however, leading to large volumes of loosely-structured data [17] with poor interoperability. The industry has became aware of data models as a way of representing technical and administrative information content, leading to the development of data structures that allow information to be exchanged among various computer applications [4]. Integration requires some degree of standardization of information representation [21]. Efforts in this line of research include those under ISO International Standards 10303, STEP

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(Standard for the Exchange of Product Model Data [15] and the Industry Foundation Classes (IFC's) developed within the International Alliance for Interoperability (IAI) [13].

This paper reports on an ongoing research project within the Construction Engineering and Management Group, Department of Civil Engineering of the University of British Columbia. This project is developing an IFC-based data model for integrated maintenance management, with a specific application to roofing systems. A case study is used to demonstrate the applicability of our proposed generic framework to integrate the management processes involved in the maintenance of all types of built assets. The IFC-based model provides a high-level representation of the information required within the management processes involved in the maintenance of built assets. The model was developed following a process-oriented methodology similar to that adopted by the IAI [13] to develop data standards in the form of IFC's.

The model also provides a direction for the potential implementation of IFC's in a maintenance management software application. It is envisaged that the intended user of the developed application would be middle-management staff dealing with operations and maintenance decision-making in a facilities management organization managing a large number of diverse assets. Their envisioned scope of responsibility includes implementing the decisions made at the strategic, tactical or operational planning windows. The strategic planning window involves the long term planning of facilities, usually beyond a five-year horizon. The tactical window looks at the tactical positioning of the organization in the two to five year frame. The operational window concerns itself with the implementation of the strategic and tactical level in day-to-day operations, normally within the current budget year [9].

2. Previous research on conceptual facilities maintenance management models

A review of literature on conceptual models for the facilities management industry indicates two streams of work which share the objective of providing better management of large volumes of loosely-structured data produced by all kinds of independently-operating facility applications. These streams are: data models for particular building systems, and data models for generic facilities management.

2.1. Data models for particular building systems

Examples of data models for particular building systems include work by Vanier [24] to develop a STEP based roofing system product model, in accordance with the planned deliverables of the Building Envelope Life Cycle Asset Management (BELCAM) project. The objective behind this model development centers on mapping input data from MicroROOFER [1], a relational database-Engineered Management System (EMS), to an object-oriented model (as illustrated in the portion of the model shown in Figure 1). A goal is to contribute to the process of standardizing the format of data collected from a number of roofing surveys to take place in North America [27]. The model addressed the development of new entities, and attributes, that were not available within MicroROOFER, but were needed to satisfy the objectives of the BELCAM project.

Karhu [16] developed a product model for precast concrete facades, aiming at enhancing the exchange of data between architects, structural engineers and precast element manufacturers. Central data structures in this conceptual schema define how a precast concrete facade consists of precast concrete elements. An element, then, consists of structural layers, which may be an outer wall panel or an insulation layer. Structural layers and openings have edges. A precast facade also has element joints and element divisions. Figure 2 provides the EXPRESS-G diagram of the main decomposition relationships of a facade.

2.2. Data models for generic facilities management

Bos's [2] work focuses on developing an object-oriented facility management information system (FMIS) with the objective of improving the quality of the working environment and prolonging the building's life-cycle. The approach adopted in developing the model treated the structure of the building as the backbone of the model. Facility management functions such as space utilization, maintenance management, and cost monitoring were applied to the building model. Items such as furniture, appliances and machinery were modeled as objects, while facility services were modeled as functions of these objects. Figure 3 displays portion of the object model of FMIS.

Underwood and Alshawi [22] propose data and process models for an integrated application, "MAINCAST", as part of an integrated construction environment prototype, "SPACE", developed at the University of Salford. The objective behind developing MAINCAST is the ability to forecast building element maintenance, during the operational years of a project's life cycle. In MAINCAST, determining a maintenance forecast, requires information on the project's individual building elements and components, which when deteriorate, develop defects that needs to be rectified. A maintenance forecast valuation for a project is collated from annual maintenance forecast valuations over the project's design life. Figure 4 displays the EXPRESS-G model for MAINCAST.

Svensson [22] proposes a Knowledge Based System (KBS) model for facilities management purposes. The KBS model was structured in five parts as follows and as illustrated in Figure 5:

KBS Core: this part has association with the three catalogue parts (2,3 and 4). It manages information on systems, spaces, and construction parts. Some of the entities in the core part include, Building, System, Technical System, Spatial System and Construction part.

Catalogue of technical systems: this part catalogues different types of technical systems in a building. Some of the entities in this part include, Earthworks, HVAC and sanitation, Electrical and Transport.

Catalogue of spatial systems: this part catalogues different types of spaces in a building. Some of the entities in this part include, Section, Storey space, Block, Room, Part of room and Area.

Catalogue of construction parts: this part catalogues different types of construction parts in a building. Some of the entities in this part include, Frame element, Plate, Lining and covering; and Opening and connection.

Work section sub model: this part manages information on the physical parts of a building and the result of a work-section process where resources are put together. Some of the entities in the part include, Soil reinforcement, Excavation or filling, Pile foundation, Trench, Pavement, Method, and labor.

Yu [28] proposes the development of Facilities Management Classes (FMC) as a similar effort in advance of, and in extension to, the Industry Foundation Classes (IFC) for facilities management domain. The intended FMCs would have similar goal as the IFCs in terms of allowing multiple applications to share and exchange project information. Some of Yu's reasoning behind introducing FMCs can be summarized as follows:

1. While the IFCs aim at representing all the common information requirements of all industry processes across all AEC/FM domains, such a broad scope has not, so far, provided enough facilities management (FM) application models to support Computer Integrated Facilities Management (CIFM).
2. The IFCs may not address as much specific detail of various FM functionality as is needed to adequately support CIFM, due to the emphasis on inter-process interoperability.
3. From an implementation perspective of FM application, some of the important FM specific information may not be modeled in the IFCs directly and explicitly, since the IFCs are not developed exclusively for FM.
4. The IFC objects contain much detail that is not needed by FM applications.
5. The IFCs represents all AEC/FM information combined together in a set of models of a much larger scope of what FM applications actually needs.

The Facilities Management (FM) Domain Committee within the United Kingdom (UK) Chapter is currently active on developing a set of IFC object models that support a number of maintenance processes [27]. The developed object models constitute their contribution to the development of IFCs within Release 2x [13].

3. The International Alliance for Interoperability

The International Alliance for Interoperability (IAI) is a global, non-profit, industry-based consortium for the Architecture, Engineering, Construction and Facilities Management (AEC/FM) industry. The goal of the IAI is to enable interoperability among industry processes of all different professional domains in AEC/FM projects by allowing the computer application used by all project participants to share and exchange project information. The scope of the IAI is the entire life cycle of the building project, covering strategic planning, design and engineering, construction, and building operation. The IAI was established with the objective of defining, publishing and promoting a specification (the Industry Foundation Classes - IFC's) which describes building project objects in a neutral computer language that represents information requirements common to all industry processes.

Since the establishment of the IAI in 1996, four IFC releases have been published: IFC release 1.0 in January 1997, IFC release 1.5 in November 1997, IFC release 1.5.1 in August 1998, IFC release 2.0 in March 1999; Release 2X is in beta review at the time of writing (September 2000). The IAI exhibits great professional diversity among its members, who come from AEC/FM industry firms, software vendors, research institutes and universities, professional organization, and government agencies. The IAI is organized into nine regional chapters worldwide, overseen by an International Co-ordination Council. Current IAI chapters include North America, German-speaking countries, United Kingdom, France, Singapore, Nordic countries, Japan, Korea, and Austral-Asian, with more than 600 members from over 20 countries. A series of domain committees, which work on a number of projects, are established within each of the chapters, based on the interests and initiatives of the members. Each domain committee represents a specialized industry sector, which then provides information requirements for the IFCs. Current classification of domain committees to date include architecture, building services, civil engineering, construction management, codes and standards, estimating, facilities management, project management, structural engineering, and cross domain projects.

The authors have participated in recent IAI/FM domain activities, including presenting the framework for a maintenance management model of critical built-assets, as addressed later in this paper. Supporting that activity, the IAI has developed some of this framework's processes within the current IFCs. Other processes that have not yet been developed--though their potential has been recognized within the IAI--include the modeling of performance requirements, recording of asset condition, and life cycle costing as a decision making criteria for maintenance, repair and renewal of critical assets.

4. Development methodology

The maintenance management data model was developed following a methodology similar to that used within the IAI [12]. The methodology began with developing initial process models and usage scenarios (discussed in the following sections), which led to defining data model extensions to the existing IFC classes.

4.1. Process Models

A process model describes the activities that exist within a business process. It defines those tasks that need to be undertaken, and illustrates how and what information needs to be communicated between tasks [5]. The IDEF_0 notation (Integration Definition for Function Modeling) is the IAI-preferred notation for the creation of graphical process models for IFC specification projects. In this representation, boxes represent tasks while arrows from the left, right, top and bottom represent inputs, outputs, controls, and mechanisms, respectively. Figure 6 illustrates the elements of a process model in IDEF_0 notation. The IDEF_0 notation was selected within the IAI because of its formal documentation support and the extensive software support [12].

4.2. Usage Scenarios

Usage scenarios, as defined by the IAI, are textual descriptions of situations that show the use of IFCs to carry out the selected process, i.e. developing a roofing maintenance management data model. They relate together the scope definition, the process model and the object classification. In usage scenarios, a set of assertions is made. The objective of developing assertions is to help identify: classes, relationships, cardinality of relationships, and attributes [12]. These assertions then can be modeled and implemented. Examples are provided later in the paper.

4.3. Object Models

An object model, according to the IAI, is a representation of the information content and structure that will be exchanged or shared [12]. Object models are used to analyze the use and design of IFCs. The IAI encourages the establishment of new modeling projects among domain committees, as can be seen from the various releases of IFCs to reflect the expansion in scope. EXPRESS-G is the preferred graphical notation of object modeling. In this notation, boxes represent classes, solid lines represent relationship between classes and heavy lines represent subtype inheritance relationships. Figures 1-5 are examples of this notation.

5. Generic framework model

The generic framework of maintenance management is described schematically as the $IDEF_0$ process model shown in Figure 6. A series of interrelated diagrams illustrating information flow from one activity to another are presented throughout the paper.

The framework model consists of five sequential typical processes [10], [11]. For each of the processes, the authors have defined a number of supporting functions, with their logical sequence and information requirements. A detailed description of the processes and the functions within is provided in the following subsections. It should be noted that every maintenance project is likely to be unique, and that some activities within each process can be omitted depending on the characteristics of the asset being examined. The five processes forming the framework 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 (referred to as node “O”).

The framework sets out policy guidelines for the conduct of maintenance in an organization. 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. 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 practice in a facilities management organization engaged in managing several assets, regardless of whether the tasks involved are implemented by in-house staff, or professional maintenance contractors.

6. IFC model architecture

6.1. Model Requirements

The IFC model architecture was developed based on the following requirements [12]:

1. Provide a modular structure to the model.
2. Provide a framework for sharing information between disciplines within the AEC/FM industry.
3. Ease the continued maintenance and development of the model.
4. Enable information modelers to reuse model components.
5. Enable software authors to reuse software components.
6. Facilitate the provision of upward computability between model versions.

6.2. IFC Model Architecture Decomposition

The architecture of the IFC model operates on four layers, following a “ladder principle”, i.e. at any layer, a class may reference a class at the same or lower layer but may not reference a class from a higher layer. Figure 7 illustrates the architecture of the IFC model.

- **Resource Layer:** provides Resources classes used by classes in the higher levels. Resources can be characterized as general purpose or low-level concepts or objects that do not rely on any other classes in the model for their existence. Resource classes may only reference or use other resources.
- **Core Layer:** provides a Core project model. This Core contains the Kernel and several Core Extensions. Core classes may reference other Core classes, and may reference classes within the Resource layer without limitations. Core Classes may not reference or use classes within the Interoperability or Domain/Application Layer. Within the core layer the “Ladder Principle” also applies. Kernel classes can be referenced or used by classes in the Core Extensions but the reverse is not allowed.
- **Interoperability Layer:** provides a set of modules defining concepts or objects common across multiple application types. Interoperability layer classes can reference classes in the Core or Resource layers, but not in the Domain/Application layer.
- **Domain/Application Layer:** provides modules tailored for specific AEC/FM industry domains or application types. Domain/Application layer classes may reference any class in the Interoperability, Core, and Resource layer.

7. Integrated maintenance management models

The purpose of developing a process model is to define requirements for information sharing amongst the various management areas. Figure 8 provides a class diagram for the roofing maintenance management model. Roofing systems, specifically flat or low-slope conventional assemblies, were chosen in the BELCAM project (http://www.nrc.ca/irc/bes/belcam) as a building system that is representative of the built-asset maintenance domain. The project is investigating service life prediction and maintenance management of building envelope components. The BELCAM project identifies maintenance management as one of the essential “enabling” technologies to permit asset managers to operate assets efficiently [27].

Figure 8 shows a collection of project-specific model elements (i.e. classes and relationships), and project-independent, or “library”, elements, which represent information that can apply across a wide range of projects.

The developed maintenance management model, while making use of existing IFCs within Release 2.0 and 2x, proposes a set of IFCs that may be considered within Release 3.0 or later. In this paper, existing IFCs within Releases 2.0 and 2x are shown in plain text, while proposed IFCs to be included in Release 3.0 or later versions are shown as underlined text. Appendix A lists the newly proposed set of IFCs.

The model in Figure 8 illustrates a roofing system (IfcRoof), a subtype of IfcProduct, can be associated with various information (in our model, we actually associate much of this information with a related IfcAsset object, which we explain later in the paper but have omitted here for simplification). The roof can be associated with a series of defined functional requirements (IfcFunctionalRequirement). The roof can be assessed against these functional requirements through inspections or "condition assessment surveys" (CAS) (IfcInspectionTask). The CAS determines the condition (IfcCondition) of the roofing system, which may, in turn, lead to a range of options to maintain, repair, or renew the existing system (IfcMRRTask). Assessment of the risks (IfcRiskSchedule) and costs (IfcCostValue) associated with a certain management option would be considered, as would the resources (IfcResource) required to execute a maintenance, repair, or renewal (MRR) task.

This approach uses "type" objects to represent "library" information. That is, project-specific objects in a project data set can reference objects that represent types of that object. For example, a specific resource, a roofing maintenance crew, can be associated with a resource type object that describes attributes typical of all roofing maintenance crews (typical crew makeup, productivity rates, unit costs, etc.). The specific crew object can inherit these values from the type object, or can define overriding values.

The concept of type objects could have many uses within the IFCs (product component types, actor types, resource types, work task types, etc.). Although the concept of type objects did not exist in previous releases of the IFCs, they have been added in IFC 2X. Also, the concept of type objects is closely related to the concept of linking objects within a project object model to additional information referenced from an external library. A project is currently underway within the IAI to investigate external library issues for the IFCs.

7.1. The "Identify Assets" model

Process Definition

The "Identify Assets" process (node "A" in Figure 6) 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 [12]. 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 [3]. Asset data are obtained from asset registers. An asset register may be defined as a table which records the assets of an organization, within which the value of all assets can be determined [12]. The inputs necessary to carry out The "Identify Assets" process are: an already existing facility and a set of resources, as displayed by the input arrows in node "A" in Figure 9. The output is a list of assets requiring maintenance. It is envisaged that the execution of this process would be optimal in Design-Build-Operate projects, where information on physical assets may be captured and recorded during both design and construction phases. Design-Build-Operate projects, is a growing trend in the construction industry in the United Kingdom [27]. As an example, in identifying a particular asset (e.g. a technical system in a building located within a campus), this process is broken down into five functions as shown in the IDEF$_0$ in Figure 9.

Usage Scenario

For the example of the roofing assets, the facility management team, through its administrative staff, carries out an inventory activity, which identifies all roofing sections to be managed. Managing roofs on the roof-section level provides a more precise means of evaluating condition and determining maintenance, repair, and renewal requirements [1]. For each roof section, the inventory contains basic information on occupancy (the building use function occurring under the roof section), section area and type of structural frame, thermal insulation, waterproofing membrane, and flashing.

The following set of assertions is made:

- A **Product** (such as **Roof**) *can play the role of* an **Asset**
- A **Roof** *contains* one or more ***RoofSection***
- A **RoofSection** *has* an ***Insulation***
- A **RoofSection** *has* a ***Slab***
- A **RoofSection** *has* a ***Flashing***
- A **RoofSection** *has* a ***Membrane***

IFC Data Model

An IfcAsset represents the fact that some object is being treated as an asset for facilities management economic and maintenance management applications. IfcAsset is a subclass of IfcGroup, and is associated with IfcInventory, also a subclass of IfcGroup, for which an inventory of assets may be carried out and defined, through the attribute “DefinedType”. IfcRoof object is treated as a type of asset. The location characteristic of the roof is determined through the location attribute of IfcBuildingElement of which IfcRoof is a subtype. The assignment relationship of an inventory to an actor is modeled by IfcRelAssignsToActor as an objectified entity carrying information on the role of the actor played within the context of the assignment to the asset(s). While the central focus of the IFCs has been on representing physical project data, the scope of the IFCs extends to representing non-physical data [6]. The IFC model in Figure 10 provides a representation of the physical things (components of the roofing system, i.e. IfcRoofSection, IfcInsulation, IfcFlashing, IfcSlab and IfcMembrane) and non-physical things (IfcInventory and IfcActor).

7.2. The “Identify Performance Requirements” model

Process Definition

The “identify performance requirements” process (node “R” in Figure 6) includes functions required to identify categories of performance requirements of an asset as a unified entity (e.g. a building), as well as the components that make-up the assembly of the asset (e.g. technical building systems). Performance may be defined as the behavior of a product related to use [14]. The scope in this process also extends to identifying performance indicators and their means of expression within each category of performance requirements. The input to this process is a list of assets (e.g. buildings and/or technical building systems and system components) 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 5 functions as shown in the IDEF_0 in Figure 11.

Usage Scenario

The facility management team, through its engineering staff, identifies the categories of performance requirements of roofing systems, as well as the performance indicators and their means of expression within each category. Performance requirements of roofing systems have been identified as water tightness, energy control, condensation control, air leakage control, load accommodation, and maintainability [19].

The following set of assertions is made:

- An **Asset** *has* one or more ***FunctionalRequirement***
- A **FunctionalRequirement** *has* a ***FunctionalRequirementType***

IFC Data Model

Figure 12 shows the data model for representing the performance requirement of an asset. If an IfcAsset object is assoicated with roof insulation, for example, an IfcFunctionalRequirementType object may be used to represent a requirement to maintain a thermal resistance value (R-value), and an IfcFunctionalRequirement object may be used to represent the specific outdoor environment. The general IFC classification system mechanism can be used to define a catalog or library of functional requirements.

To tie into the current release of the IFC model (Release 2X), IfcFunctionalRequirement can be associated with IfcProperty, which is an abstract generalization for all types of properties that can be associated with IFC objects through the property set mechanism. Similarly, IfcFunctionalRequirementType can be associated with IfcPropertyDefinition, which defines the generalization of all characteristics (i.e. a grouping of individual properties) that may be assigned to objects.

7.3. The "Assess Performance" model

Process Definition

The "Assess Performance" Process (node "P" in Figure 6) includes functions required to determine the deviation in the performance of the asset, 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 cease to meet the performance requirements specified in process (R) and, hence require a maintenance, repair, renewal, or "do nothing" action. Maintenance includes general activities such as cleaning drains, removing obstructions in roofs, and replenishing depleted protection fluids in mechanical equipments. Repair includes unplanned intervention activities, performed to rectify situations of distresses found. Renewal include activities to install a new asset and/or component to replace the one in-place, due to economic, obsolescence, modernization or compatibility reasons [25]. One example would be installing a new assembly of roofing system either above the existing system, or after disposing of the old roofing system. “Do nothing” includes postponing or ignoring maintenance, repair or renewal. 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 specify a set of actions when a specific set of conditions occur. This process is broken down into four functions as shown in the IDEF$_0$ in Figure 13.

Usage Scenario

The facility management team, through its specialist members (roofing trade), carries out one or both of the following scenarios: (a) a preventative maintenance action, represented as a scheduled condition assessment survey for predefined components of the roofing assembly, at predefined frequencies, to inspect the condition of the roof visually, assess its condition, and record anomaly severity level and quantity, (b) a corrective maintenance action, which is generated from a request by an facility user to rectify anomalies found on the roof. A recommendation to maintain, repair, or renew (MRR) the existing roofing system is made based on the observations recorded and condition rating of the roofing assembly.

The following set of assertions is made:

- An **InspectionOrder** *orders* one or more ***InspectionTask***
- An **InspectionTask** *has* a ***Frequency***
- An **InspectionTask** *requires* one or more ***InspectionTest***
- An **InspectionTest** *has* an ***InspectionResult***
- An **InspectionResult** *determines* a ***Condition***
- A **Condition** *dictates a* ***MRRTask***
- A **RoofSection** *requires* one or more ***MRRTask***

IFC Data Model

As shown in Figure 14, the point at which an inspection is initiated is modeled as an IfcInspectionOrder, a subtype of IfcControl. An inspection activity (IfcInspectionTask), a subtype of IfcProcess, then takes place and a particular inspection method (IfcInspectionTest) is conducted, thus resulting in some inspection result (IfcInspectionResult). IfcProcess represents any general actions taking place in completing a work of design,, construction, or facilities management [7]. IfcInspectionTask, is intended to describe the work processes that make up performance assessment of assets. Information such as schedule dates and duration is defined in IfcInspectionTaskType. The current condition (IfcCondition) can be then inferred from the inspection result. Determining the condition of a roof section dictates the need for a maintenance, repair, or renewal activity (IfcMRRTask).

7.4. The "Plan Maintenance" model

Process Definition

The "Plan Maintenance" process (node "M" in Figure 6) includes functions that are required to determine maintenance priorities based on conflicting management objectives. These objectives are:

a. Minimizing maintenance cost: This objective is treated through performing a life cycle costing analysis to predict initial and future expenditures associated with a maintenance operation over the life cycle of an asset.
b. Maximizing asset performance: This objective is treated through predicting the performance of an asset for each of the maintenance options. One method of performance prediction 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 [18].
c. Minimizing risk of failure: This objective is treated through concurrently considering the probability of failure and the consequences of failure. One method of calculating 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 [18] 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 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 completion. This process is broken down into 5 functions as shown in the $IDEF_0$ in Figure 15.

Usage Scenario

The facility management team, through its feasibility analysts, evaluates the recommendation for carrying out MRR, taking into consideration a range of conflicting management objectives. These objectives are minimizing cost, minimizing the risk of roof failure, and maximizing the performance of the roof based on the remaining service life [18].

The following set of assertions is made:

- A **RoofSection** *requires* one or more ***MRRTask***
- A **MRRTask** *has* one or more ***CostValue***
- A **CostValue** *has* one or more ***CostSchedule***
- A **RoofSection** *has* one or more ***RiskSechedule***

IFC Data Model

The IfcRiskSchedule (See Figure 16) represents a collector class for the risks associated with a roofing section. These risks are evaluated through concurrently considering the probability of roofing system failure and the consequences of failure. In this process, an evaluation of costs is also considered. Cost information (IfcCostValue) is represented as being related to the object being costed (IfcRoofSection) and to a cost schedule document (IfcCostSchedule) that describes the context of a list of cost values. The entity IfcCostSchedule can be used to represent any form of cost list, such as an estimate, a budget, or a unit price table [7].

7.5. The "Manage Maintenance Operations" model

Process Definition

The "Manage Maintenance Operations" process (Node "O" in Figure 6) includes functions that are required to support the execution of maintenance operations and the implementation of maintenance, repair and 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 the IDEF$_0$ in Figure 17.

Usage Scenario

The facility management team, through its engineering staff, allocates resources to carry out a MRR task. Resources include subcontractor, equipment, material, and labor. The staff also determines MRR work methods as well as schedule date and duration.

The following set of assertions is made:

- A **RoofSection** *requires* one or more ***MRRTask***
- A **MRRTask** *has* a ***MRRTaskType***
- A **MRRTask** *uses* one or more ***Resource***
- A **Resource** *has* a ***ResourceType***

IFC Data Model

In modeling maintenance processes, the association between processes and the products upon which they operate is illustrated through using an objectified relationship entity named IfcRelAssignsToProcess. As shown in Figure 18, a roof section (IfcRoofSection) is being assigned to undergo a maintenance, repair or renewal task (IfcMRRTask). IfcResource (and its subclasses such as IfcMaterialResource, IfcEquipmentResource, IfcLaborResource, etc.) represent the resources used to complete a maintenance, repair or renewal task (IfcMRRTask). Since processes use resources, the resource-use relationship is represented through the objectified entity IfcRelUsesResource, which stores information on resource use, duration, quantity, waste factor and costs [6].

8. Roofing maintenance management example

This example identifies typical maintenance management tasks and provides example project. In this example, Unified Modeling Language (UML) [20] was selected since EXPRESS-G, the notation used for class diagrams within the IAI, contains no notation for representing object (i.e. instance) diagrams (Froese et al. 1999). While classes represent real world items of interest through collections of attributes and relationships, instances represent specific, individual set of values for the attributes and relationships. In particular, while the data models in figures 10, 12, 14, 16 and 18 define the classes used in developing the roofing maintenance data models, project scenarios in figures 19-23 define instances of these classes to represent the data used for the scenarios. Some intermediate objects have been omitted, and a few other minor simplifications have been made for clarity.

8.1. Identifying roofing system components scenario

Figure 19 illustrates a UML object diagram that identifies roofing system components. In this scenario, a roof is treated as an asset, which is listed in an inventory. The roof is comprised of several roof sections. For one of the roof sections, associated insultation, membrane, flashing, and slab objects are shown.

8.2. Identifying performance requirements scenario

Figure 20 illustrates a scenario for identifying performance requirements of roofing systems. The figure illustrates that a roof asset may have one or more functional requirement such as water tightness and energy control. The context attribute in these objects refer to the relevance of application of the functional requirement to either a building element or a building space.

8.3. Performance assessment scenario

Figure 21 illustrates a UML object diagram for a roofing system performance assessment scenario. In this scenario, the condition of the roof section is dependent on the collective condition of the roofing system components, i.e. the condition of the roofing membrane and the condition of the roofing insulation.

8.4. Maintenance planning scenario

Figure 22 illustrates a UML object diagram for a roofing maintenance planning scenario. The scenario illustrates that a roof section may have one or more risks associated with it.

8.5. Maintenance operations management scenario

Figure 23 illustrates a roofing maintenance operations scenario. The scenario illustrates that a minor repairs task (IfcMRRTask) may need one or more resources for its completion.

9. Conclusions

The paper presents a proposed generic framework for integrating the management processes involved in the maintenance of built-asset with an example application to roofing systems. The framework sets out policy guidelines for conducting maintenance in an organization. It presents a solution to bridge the gaps in the practice of maintenance of critical assets by asset managers. The framework is schematically described as an $IDEF_0$ process model.

The research has generated a robust set of data standards, considering existing standards and representations, which can be used by all participants in a facilities maintenance management project. The set of data model schemas are shown in EXPRESS-G graphical notation.

The framework allows incremental development of industry processes, leading to development of additional data standards. Thus allowing users to develop their own information systems, while maintaining interoperability with each other. It is envisaged that while the developed data standards supports information exchange within the FM domain, they are capable of being re-used, hence supporting information exchange between different domain areas. This is due to the requirement of the modular structure that the data standards satisfies.

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Appendix A

Proposed set of IFCs to be included in Release 3.0 or later versions:

IfcRoofSection
IfcFlashing
IfcMembrane
IfcFunctionalRequirement
IfcFunctionalRequirementType
IfcCondition
IfcInspectionOrder
IfcInspectionTask
IfcInspectionTest
IfcInspectionResult
IfcMRRTask
IfcMRRTaskType
IfcRiskSchedule
IfcResourceType
IfcConditionType

List of Figures

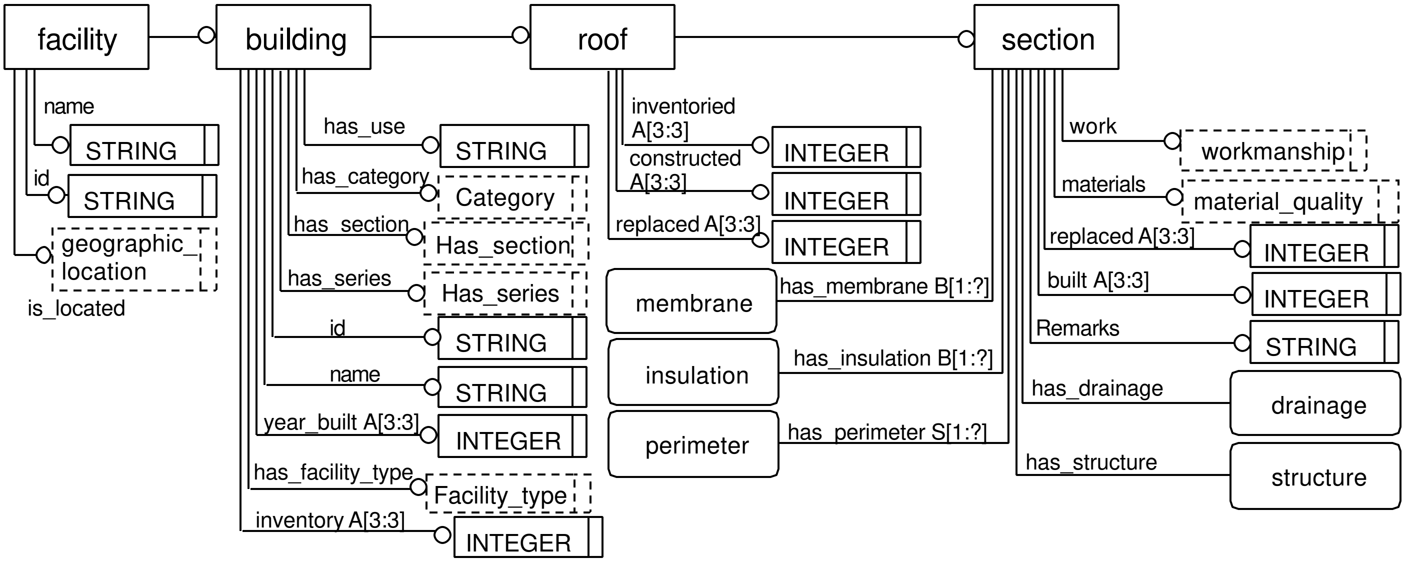

Figure 1: Portion of roofing system product model [24]

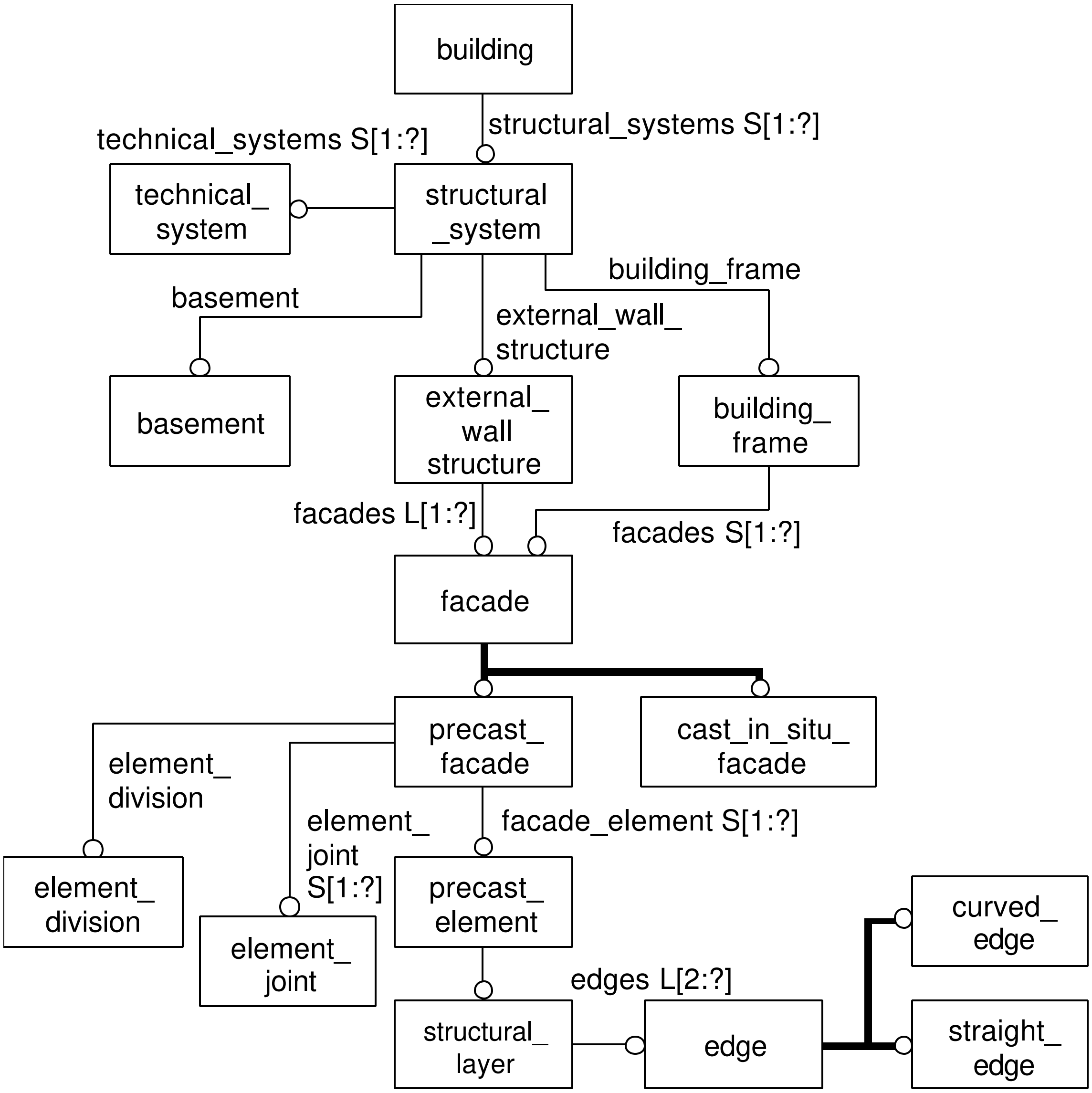

Figure 2: Main decomposition relationship of a facade [16]

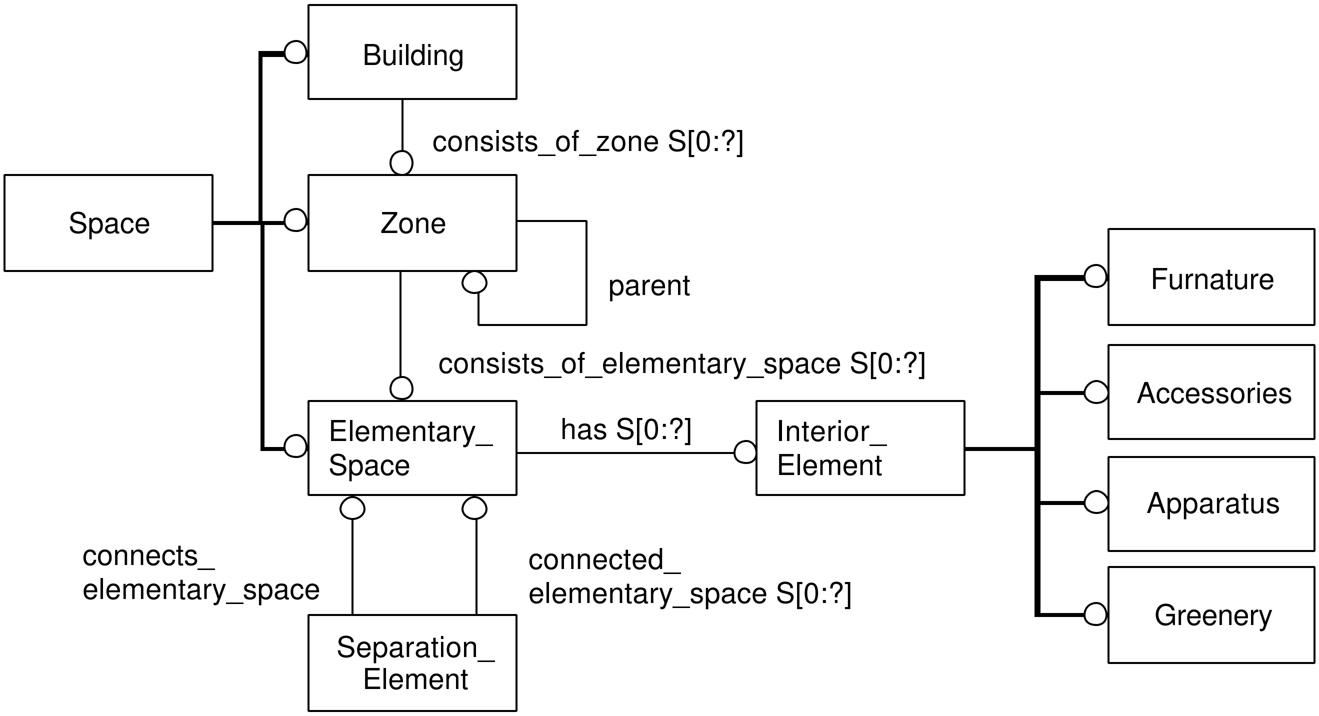

Figure 3: Portion of the object model of FMIS [2]

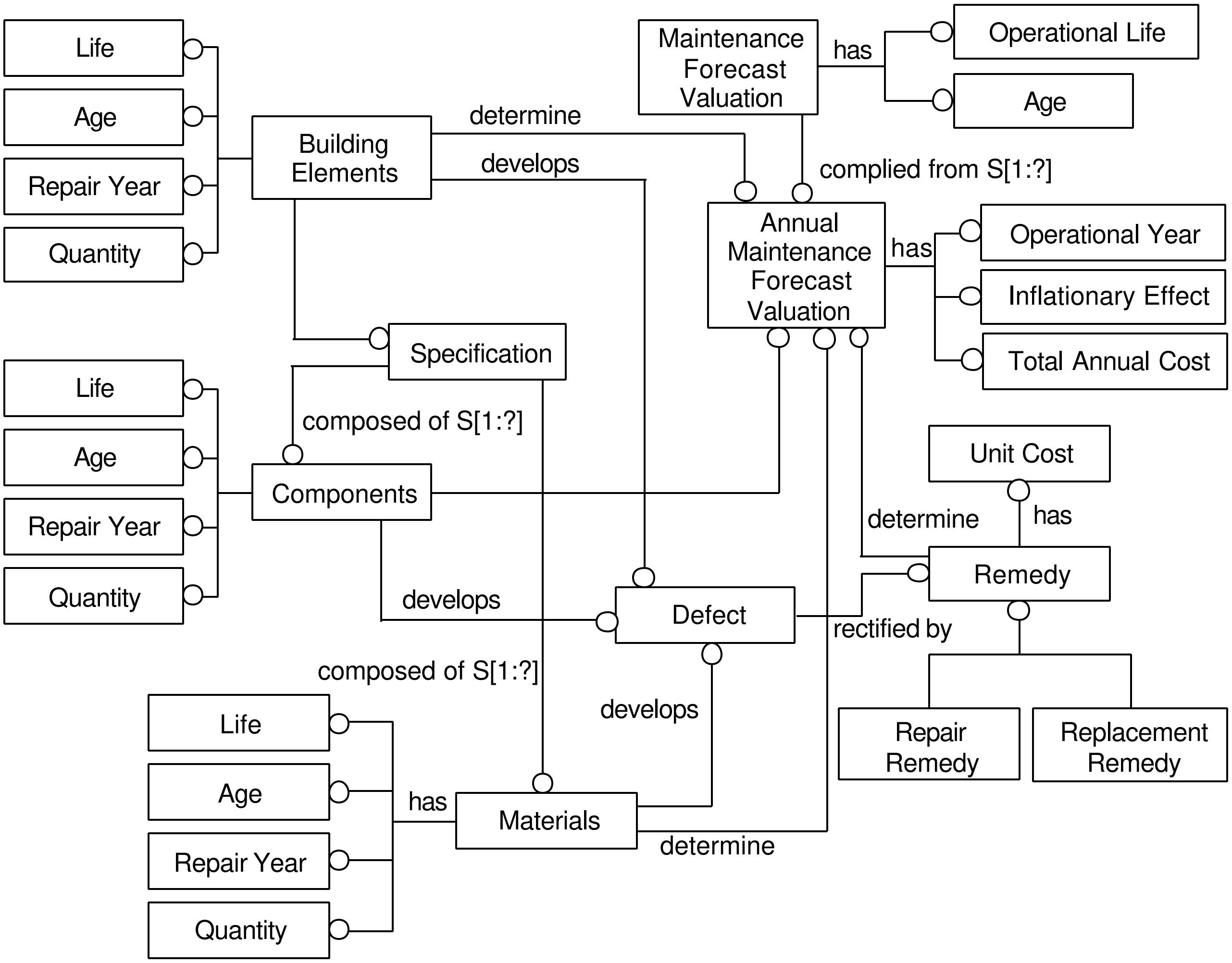

Figure 4: EXPRESS-G model for MAINCAST [23]

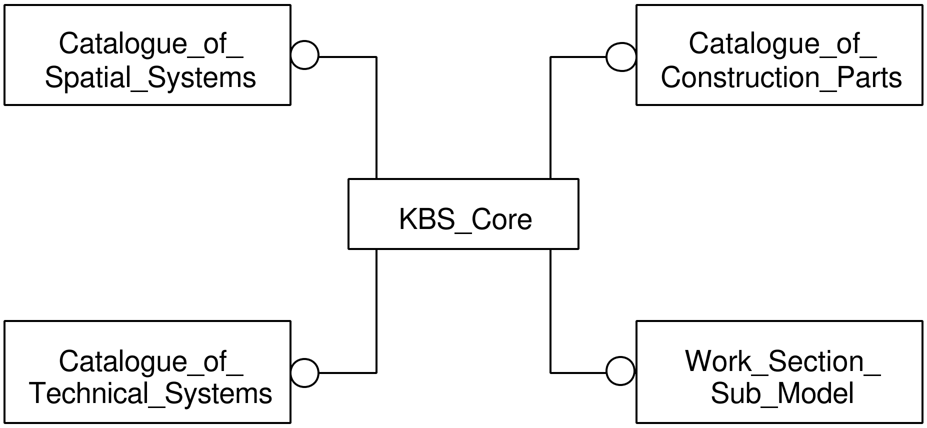

Figure 5: The schematic structure of the KBS model [22]

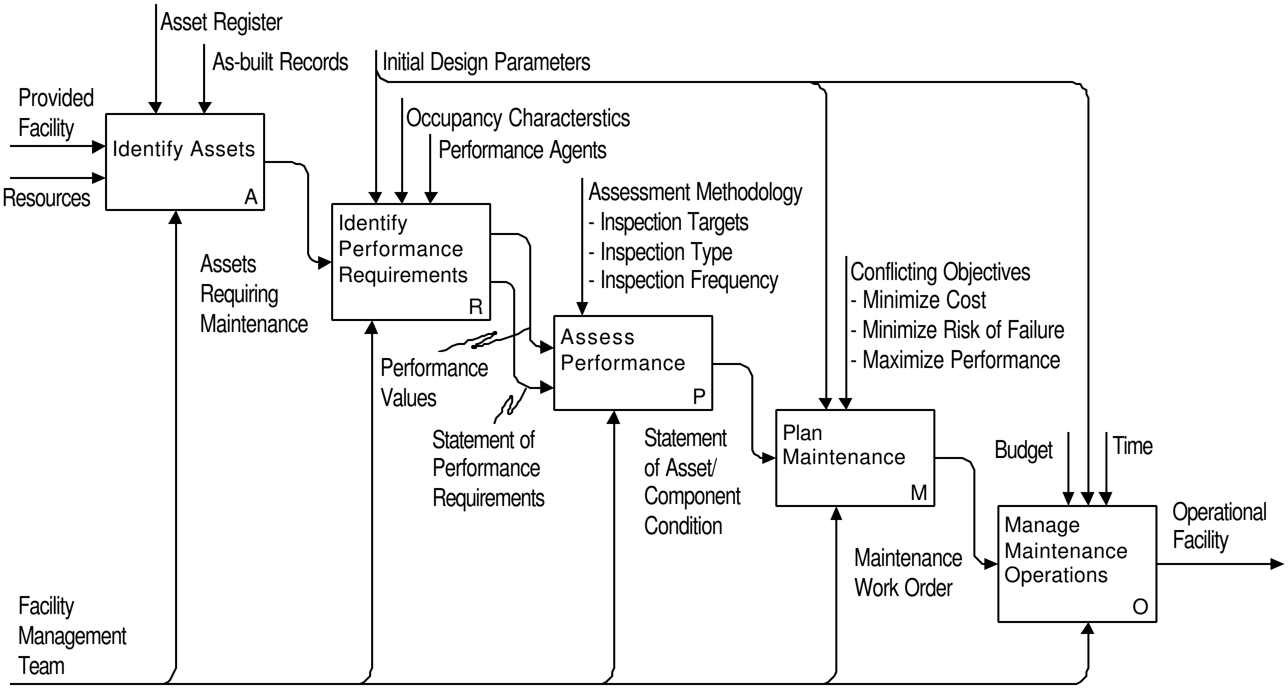

Figure 6: General processes involved in maintenance management model

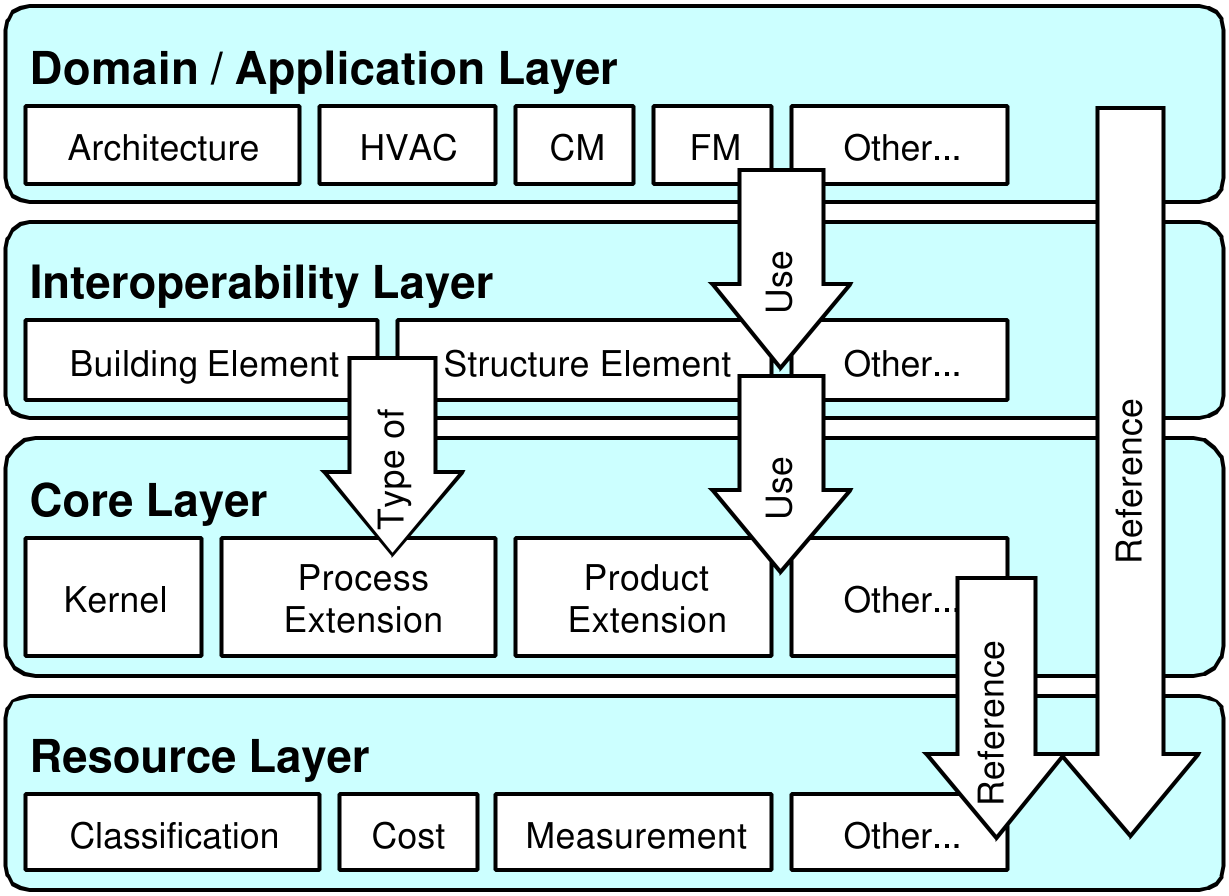

Figure 7: IFC Model layer

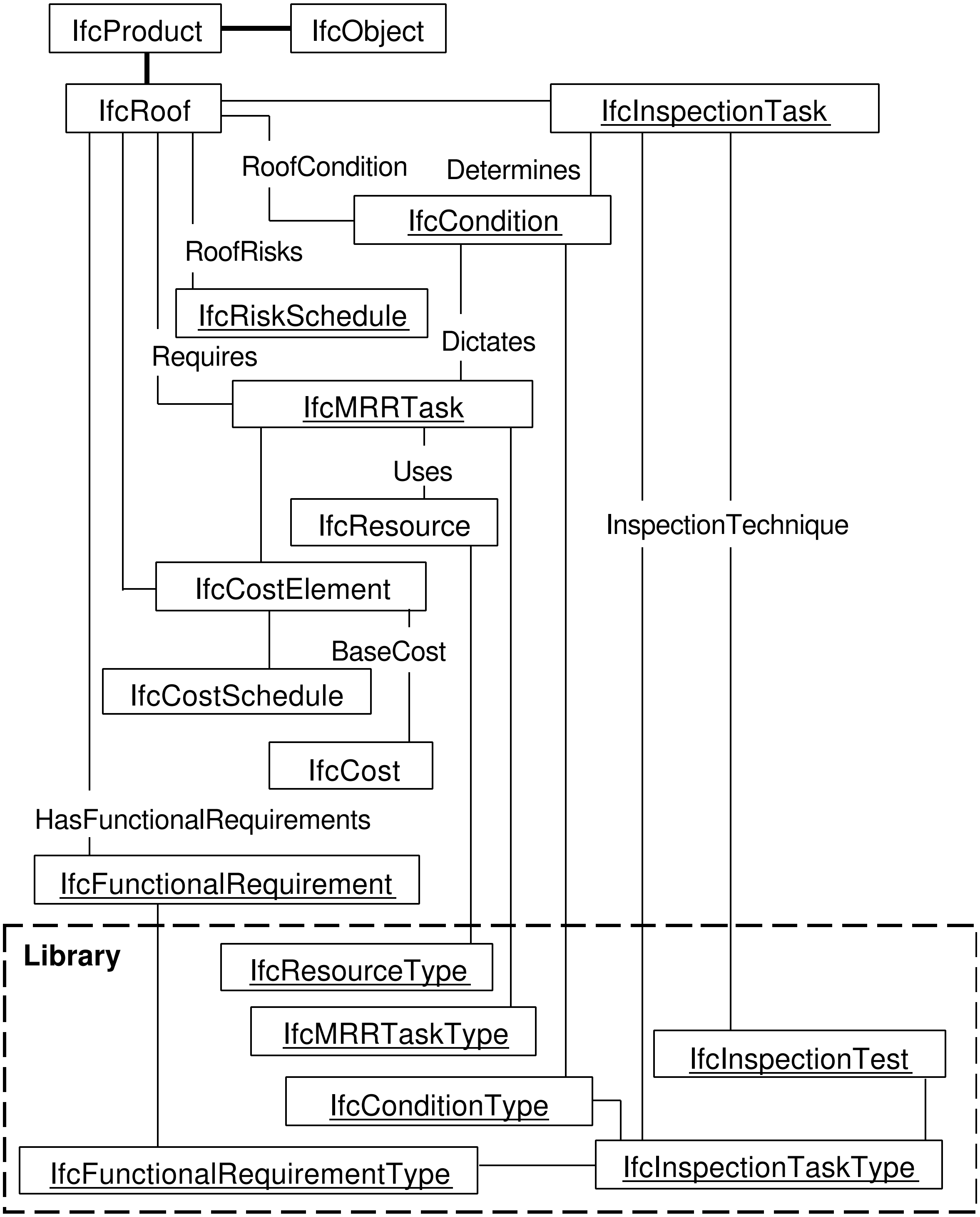

Figure 8: Overview of roofing maintenance management data model

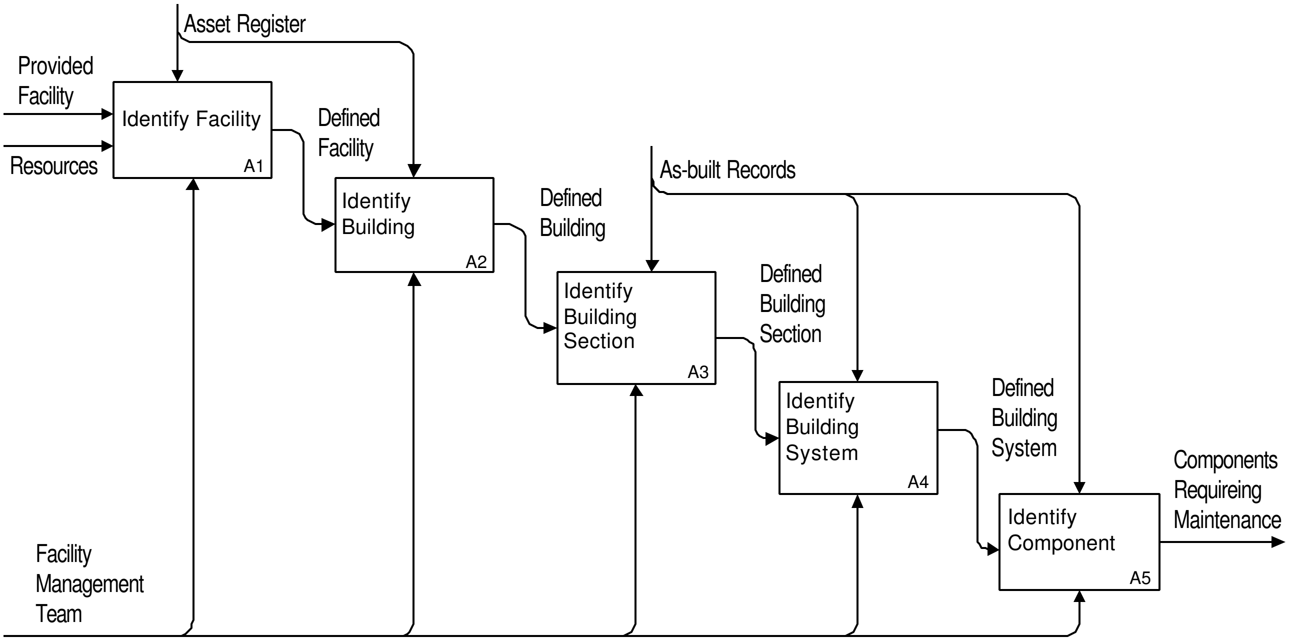

Figure 9: Node A, identify assets

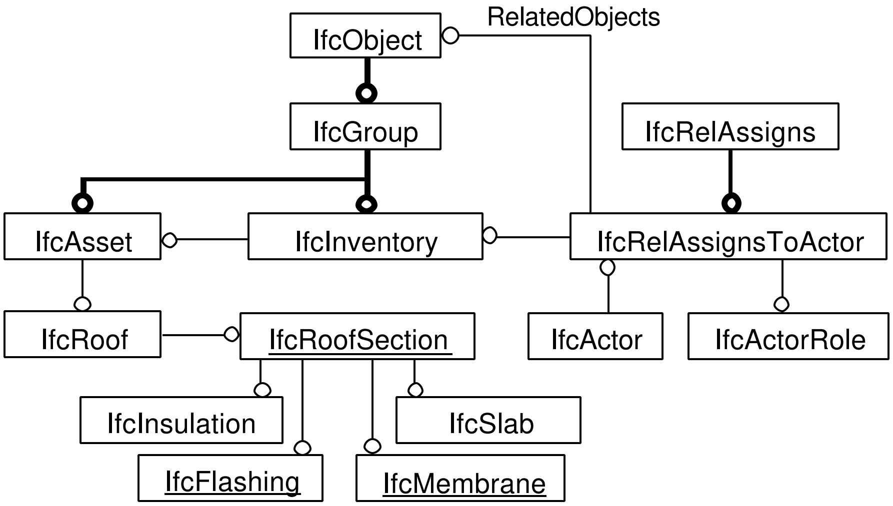

Figure 10: IFC Model for identifying roofing system components

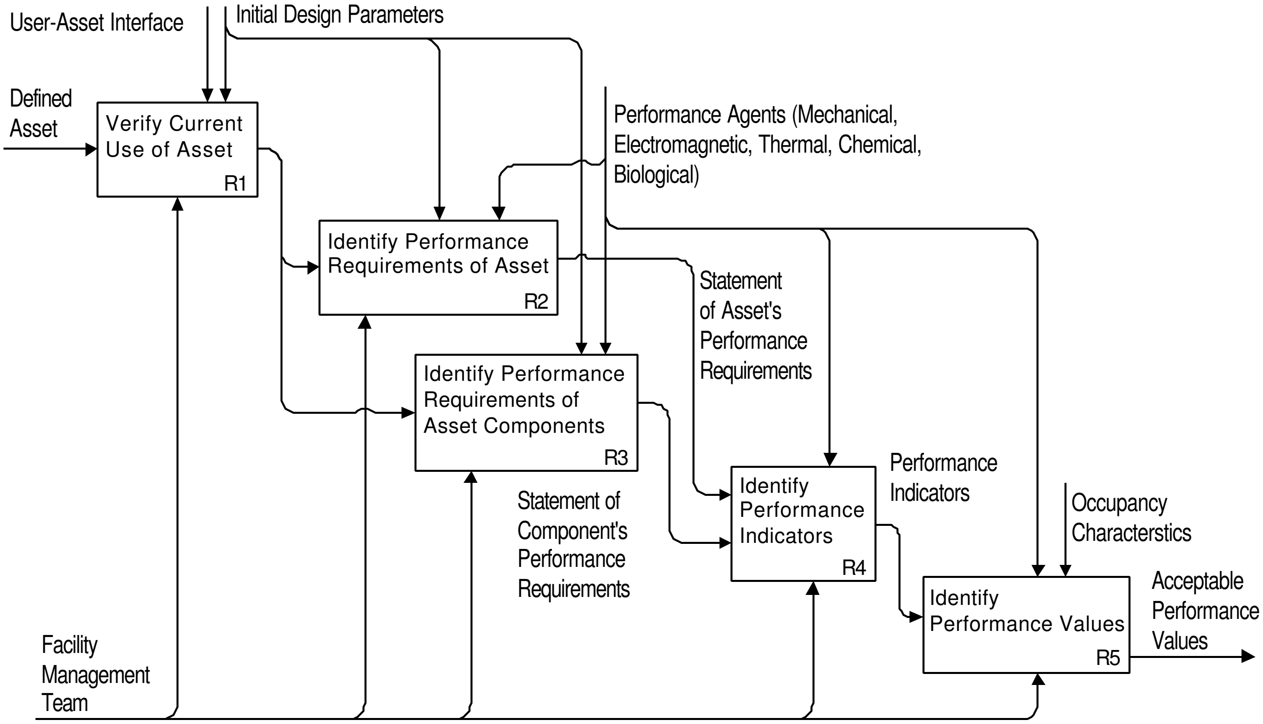

Figure 11: Node R, identify performance requirements

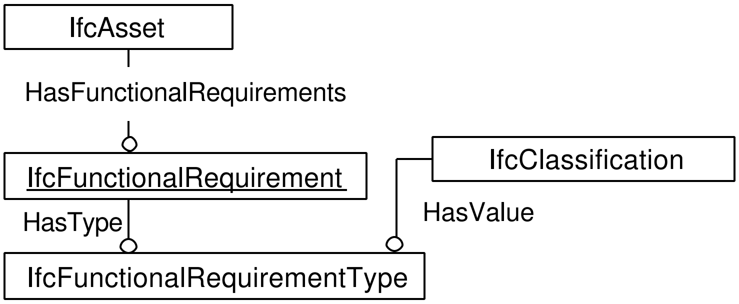

Figure 12: IFC Model identifying performance requirements of roofing systems

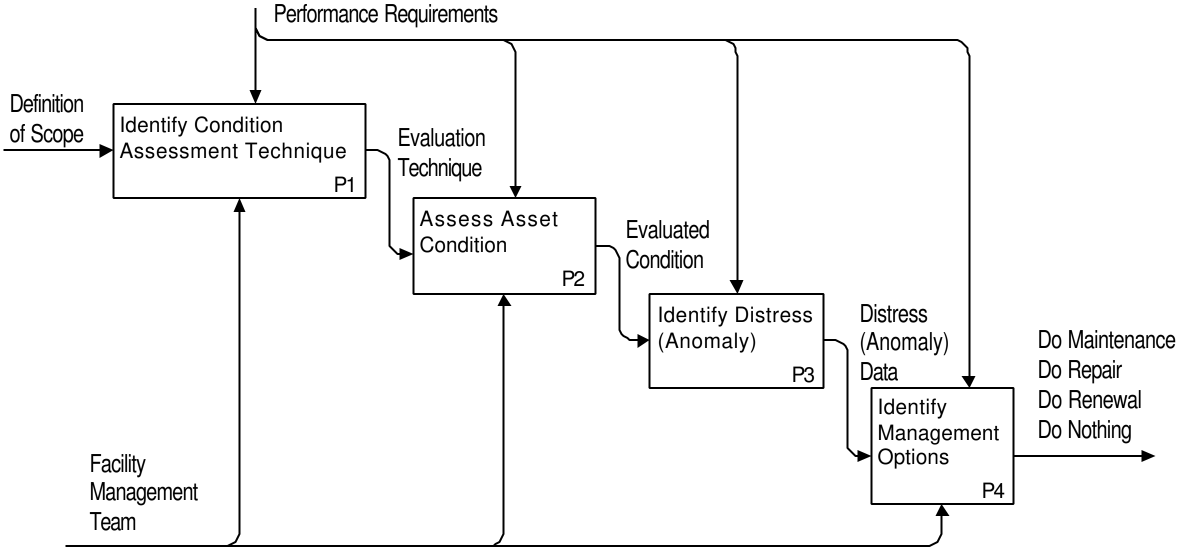

Figure 13: Node P, assess performance

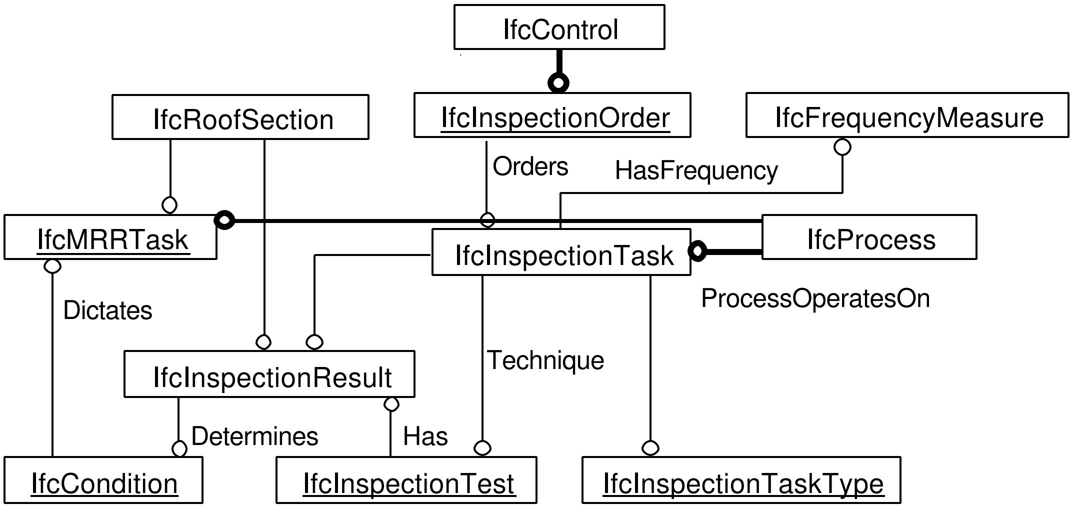

Figure 14: IFC Model for performance assessment

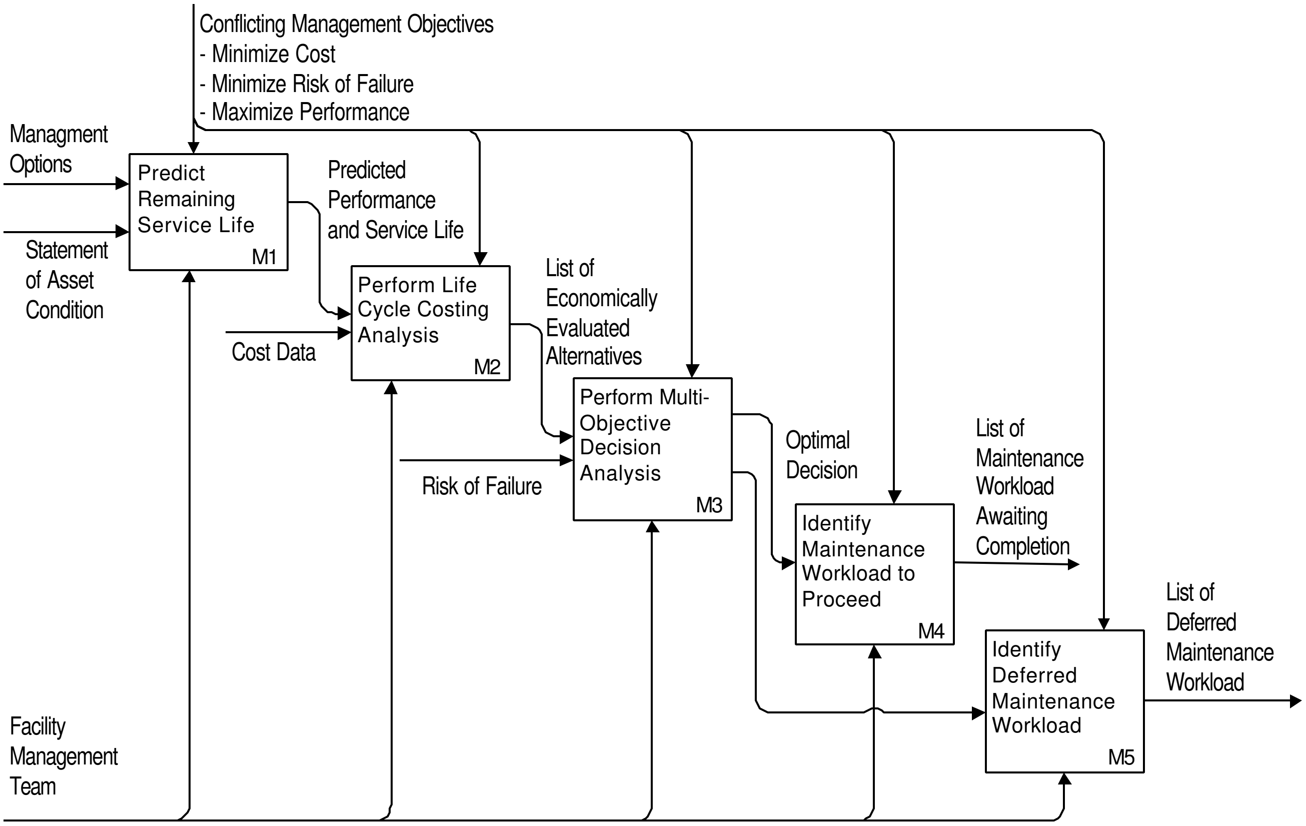

Figure 15: Node M, plan maintenance

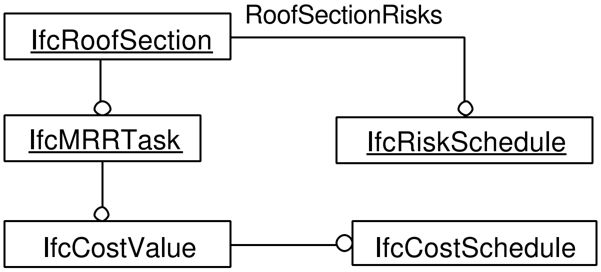

Figure 16: IFC Model for maintenance planning of roofing systems

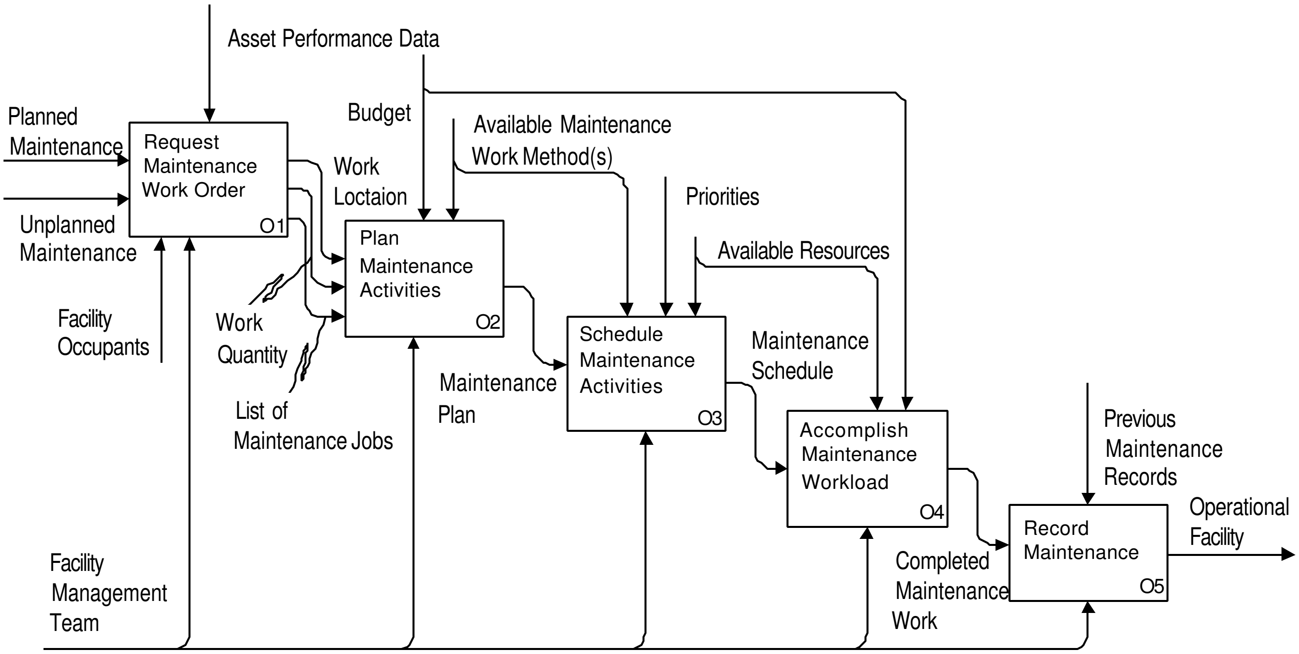

Figure 17: Node O, manage maintenance operations

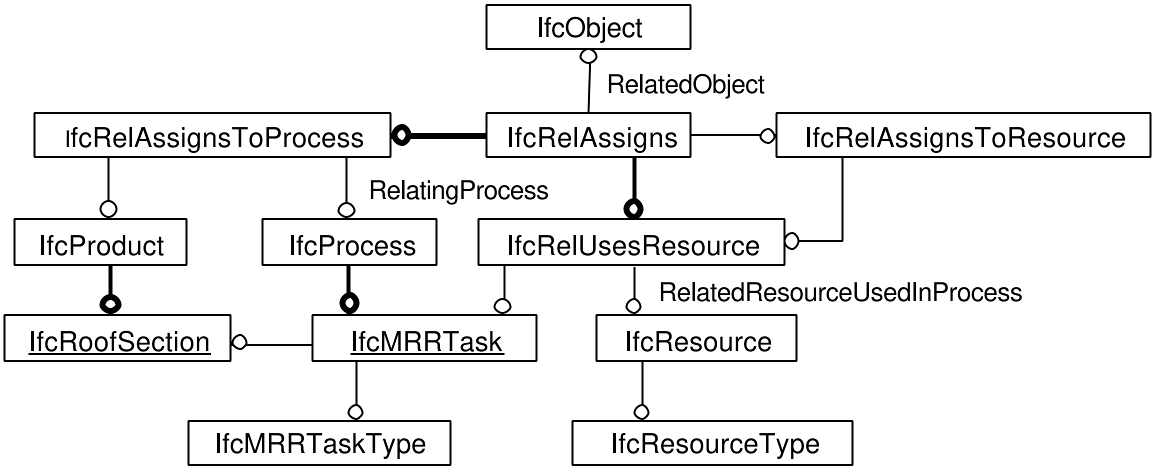

Figure 18: IFC Model for roofing system maintenance operations management

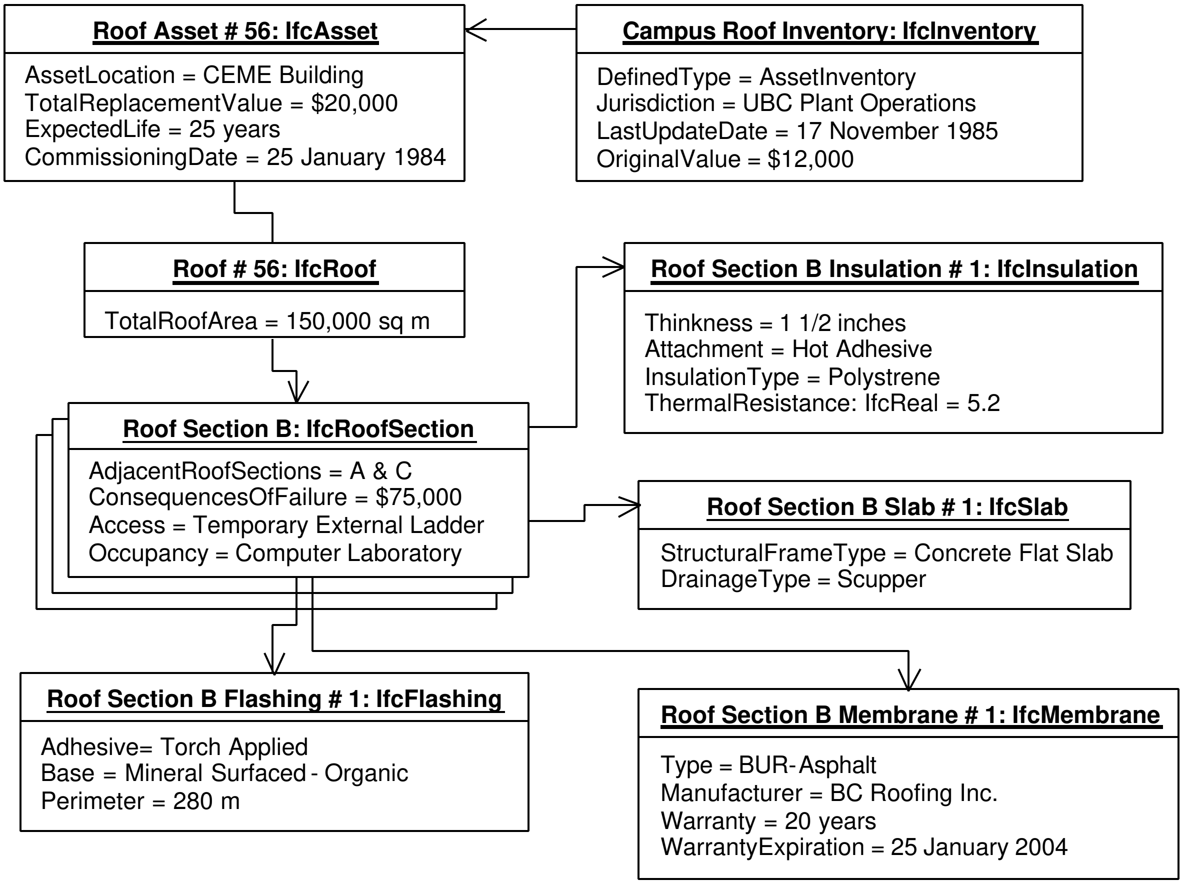

Figure 19: UML object diagram for the scenario of identifying roofing system components

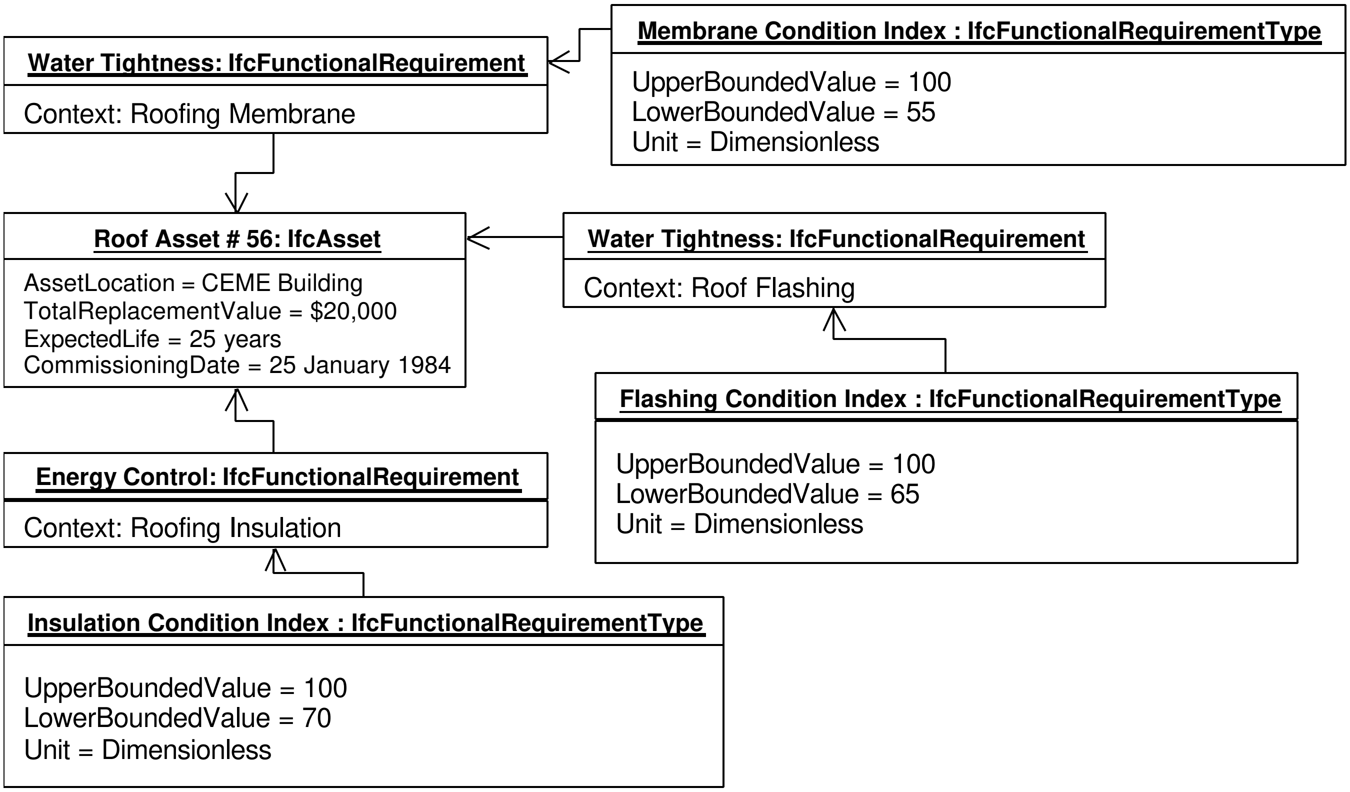

Figure 20: UML object diagram for the scenario of identifying performance requirement of roofing systems

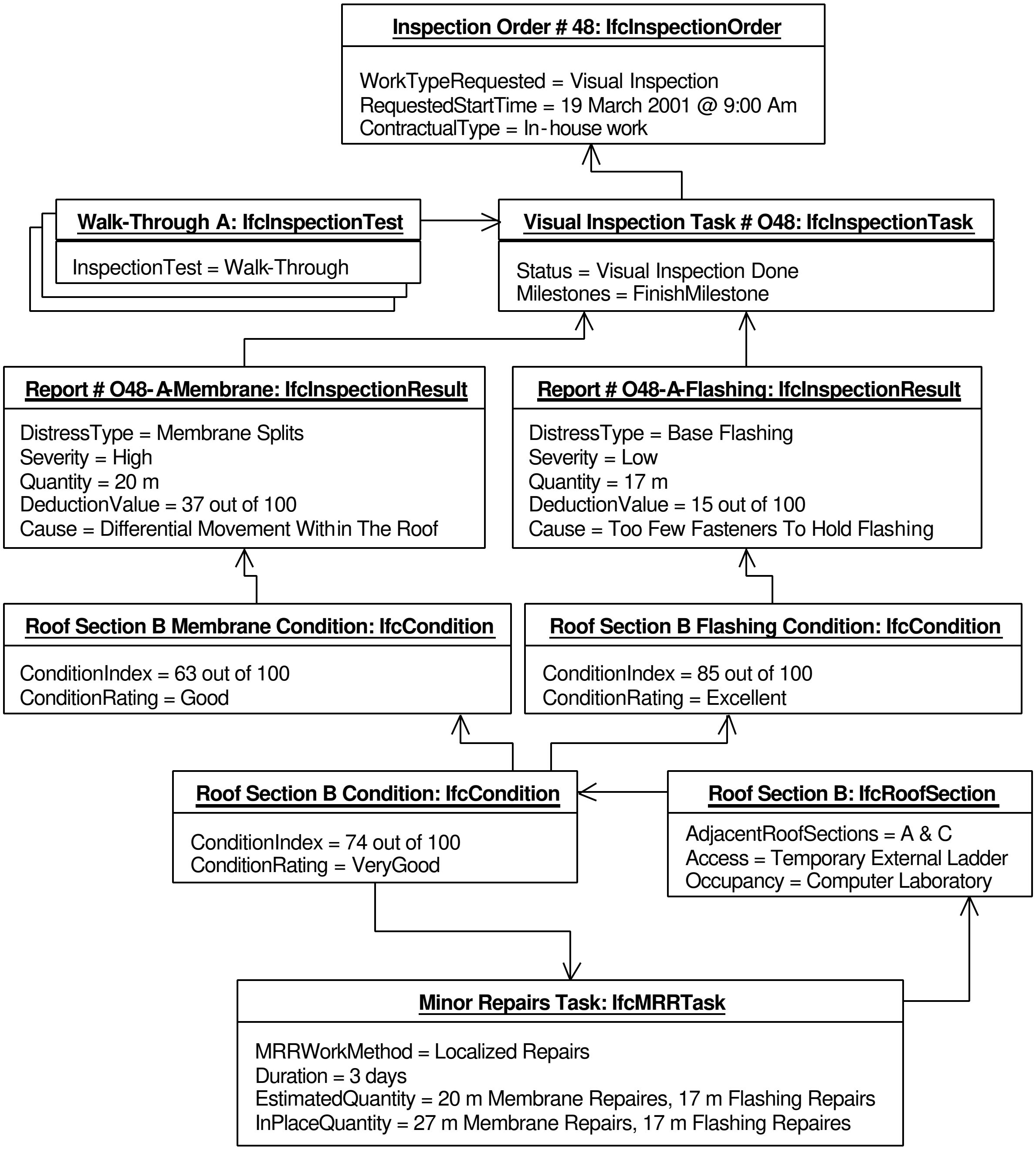

Figure 21: UML object diagram for the scenario of performance assessment of roofing systems

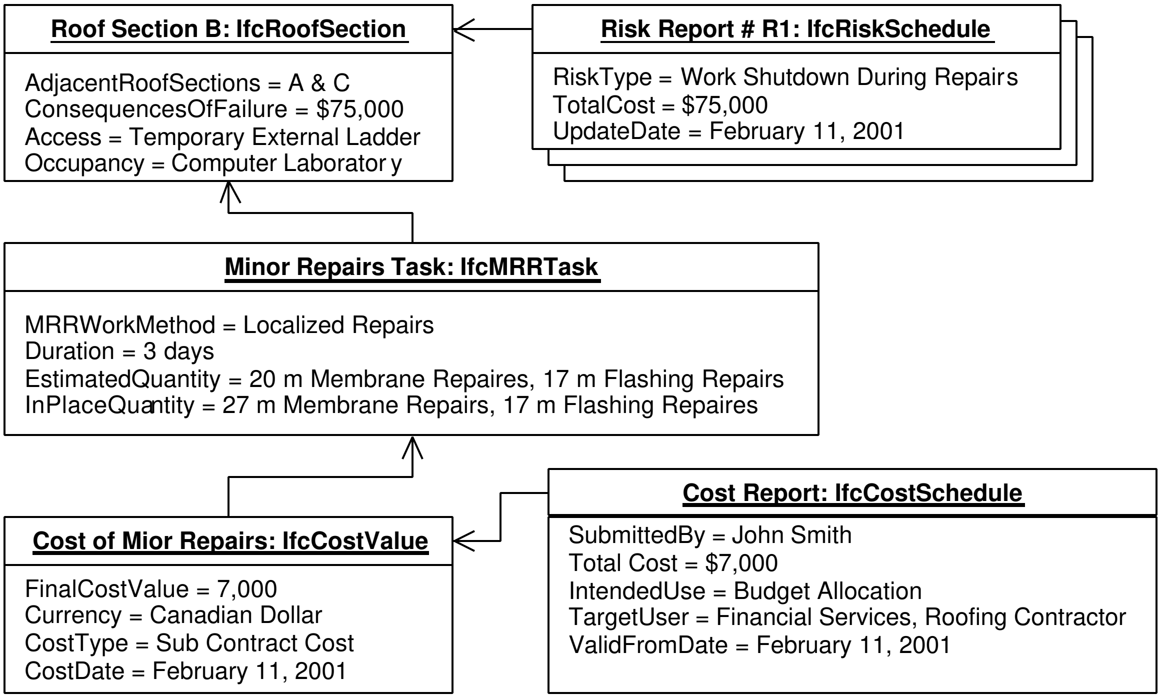

Figure 22: UML object diagram for the scenario of roofing maintenance planning scenario

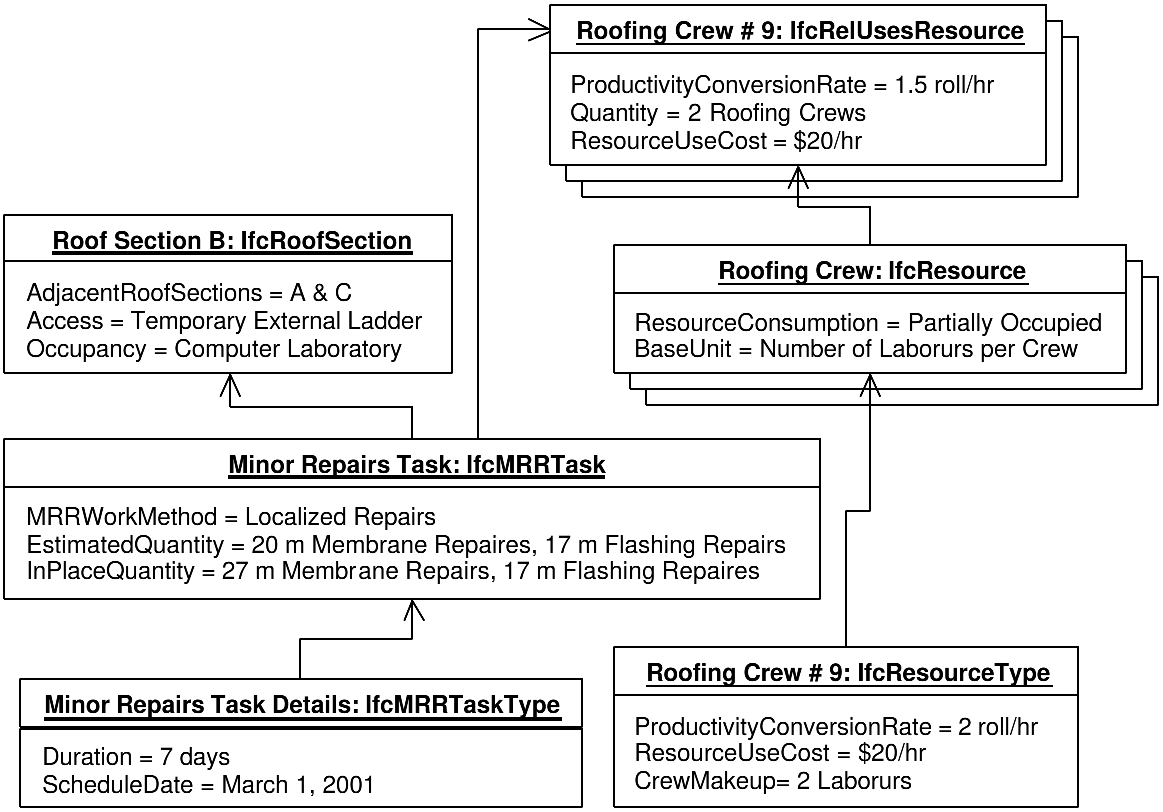

Figure 23: UML object diagram for the scenario of roofing maintenance operations management